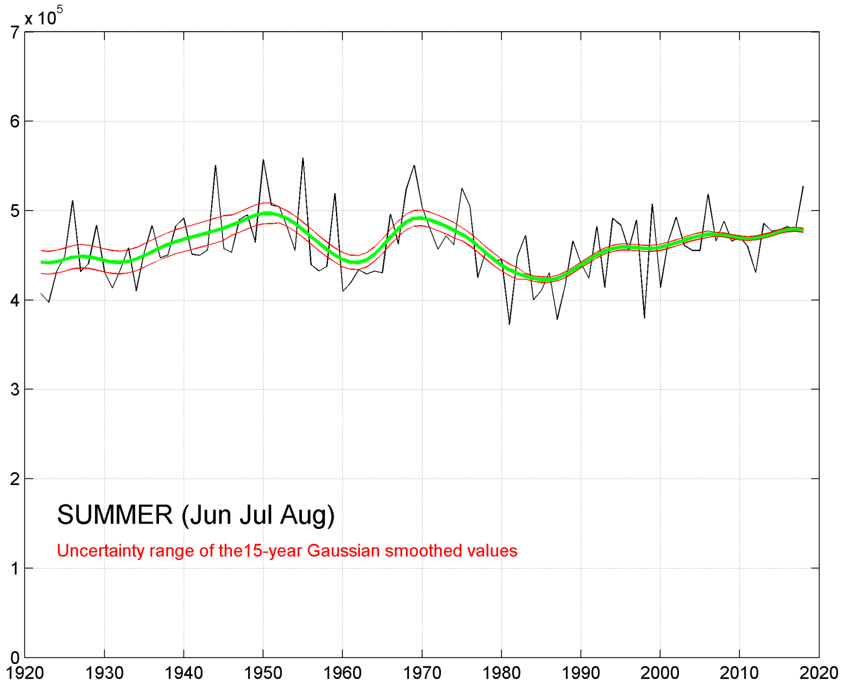
METEOROLOGY No. 165

Long-term global radiation in Stockholm, 1922-2018

Weine Josefsson



Front:
Global irradiation for the summer months (June, July and August) in Stockholm 1922-2018. Also plotted are Gaussian smoothed values with estimated uncertainties.

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Summary

In 1922 monitoring of global irradiation started in Stockholm, Sweden. Over the years SMHI has been measuring this meteorological quantity with various instruments and at different sites within Stockholm. This type of changes of instruments and sites cause minor, but important systematic changes in the measured global irradiation. Therefore, it is not recommended to directly compare the results from different periods.

The report presents methods how this can be done and there is a final data set with long-term global radiation data for Stockholm. Daily and monthly final data are presented on a web-page at www.smhi.se

As a bi-product the sunshine duration was also digitized, controlled and corrected. These data can be found in Appendix 3.

Sammanfattning

År 1922 inleddes mätningar av globalstrålningen i Stockholm. Under åren har SMHI använt olika instrumenttyper, insamlingssystem och även flyttat mätplatsen inom staden. Denna typ av förändringar orsakar, små ibland större, men betydelsefulla systematiska förändringar i den uppmätta globalstrålningen. Därför kan det finnas betydande osäkerheter i direkta jämförelser av data från olika perioder. I föreliggande rapport visas hur data granskats, ibland rättats, kompletterats och korrigerats för kända mätfel till ett slutligt data-set, som förhoppningsvis bättre ska kunna användas för studier av den långsiktiga variationen av globalstrålning i Stockholm än de ursprungliga mätningarna.

Under arbetet uppstod behov av att använda solskenstidsobservationer. Dessa har därför digitaliserats, granskats och vid behov rättats så att en någorlunda homogen serie erhållits på månadsnivå. Information om detta finns i Appendix 3.

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1 Introduction

In Stockholm, Sweden, the global radiation has been measured for almost one hundred years. In a global perspective this is rather unique. However, the monitoring conditions have varied and instruments have changed over the period. The first measurements were operated on top of a villa in a suburban area by Aurén (see e.g. Ångström, 1928) using an Ångström pyranometer. And starting in 1945 the Swedish Meteorological and Hydrological Institute began the still ongoing measurements.

All these measurements have been published as monthly values and for some periods even as daily and as hourly values. Over the years the site has changed as well as the units and the so called radiation scale which data refers to. The published data as they are may not be comparable over time; i.e. data are not homogenous, because instruments have different characteristics and the data handling methods has varied over the years. If trends are presented the result may be incorrect as some effects inherit time dependent systematic errors.

This report tries to estimate and correct for these imperfections to get a more consistent and homogenous data set, so various time periods may be compared. Some periods have proved to be hard to find out exactly how the measurements have been done. And thus the corrections applied for some periods are inherited with a larger uncertainty than it is for other periods. However, it is assumed that the application of a correction has on average improved the final result.

The final data sets are presented on the web, where they can be downloaded freely.

Figure 1.1 The present location at Stockholm-KTH as it was equipped from 1983 to 2006. Since then the wind measurements have stopped and also the measurements of the direct solar radiation including sunshine duration using a pyrheliometer. The pyranometer, Kipp and Zonen CM11, is located to the left (south) on the platform.

2 Meta data for the Stockholm series

In the following sections some basic metadata is presented and compiled in tables to give an overview.

2.1 Available raw data

Global radiation data from Stockholm has been published. But, in this project one aim has been to find the most original source and the highest time resolution possible. These data has been digitized to enable simple processing. In Appendix 1 is a table that shows what temporal resolution that is available over the years.

In the early days there might only be monthly values available. And then there are daily values and from later years hourly values can be found.

It should be mentioned that there is a long period with registrations of every second minute on paper (strip chart rolls) 1957-1983. These can be found in the archive of SMHI and they have been evaluated and digitized to hourly values.

2.2 Sites

Unfortunately, the measuring site has moved a couple of times within Stockholm. The maximum distance is about 7 km between Bromma – Stocksund and between Bromma – Royal Institute of Technology (KTH). The present site at KTH is located about 3.5 km from Stocksund and 3 km from Fridhemsplan. How, these position changes may have influenced the global radiation has not been possible to find out using the available data. It is therefore assumed to be negligible.

During the first period 1922-1945 the measurements were done by Dr. T. Aurén on the roof of his suburban villa in Stocksund, Ångström (1926) and Aurén (1930). The surroundings were other villas and gardens. According to Aurén the horizon was almost completely free with the exception of a tower in the east. He also pointed out that the air in general was much cleaner in Stocksund than in central Stockholm. At that time all buildings were heated separately during the winter mostly by burning wood or charcoal.

In 1945 the monitoring was moved from Stocksund to SMHA (present SMHI). The instrument was put on the roof of the office building at Fridhemsplan, which is a more urbanized location in Stockholm. The nearest neighborhood is typically other roofs and streets. The horizon was probably free. The photo below from 1975 shows the view towards south.

Figure 2.1 Photo taken at the site Stockholm-Fridhemsplan in the year 1975 in direction south to south-east. To the left there are three instruments standing on metal plates attached to the wooden base. Two Kipp & Zonen CM5 are used to record global radiation and diffuse radiation. In between there is an instrument measuring the illumination. Photo: SMHI.

As SMHI left Stockholm and was relocated to Norrköping in 1975 the measurements of global radiation for Stockholm were moved to the nearby airport of Bromma (Stockholm). The surroundings here can be characterized as a typical city airport.

In 1983 the solar radiation network of Sweden was upgraded and the measurements in Stockholm were moved to a roof at the Royal Institute of Technology (KTH) where it still resides in 2018. The surroundings are other roofs but also some green areas. A new upgrade was done in 2008 but the site remained the same.

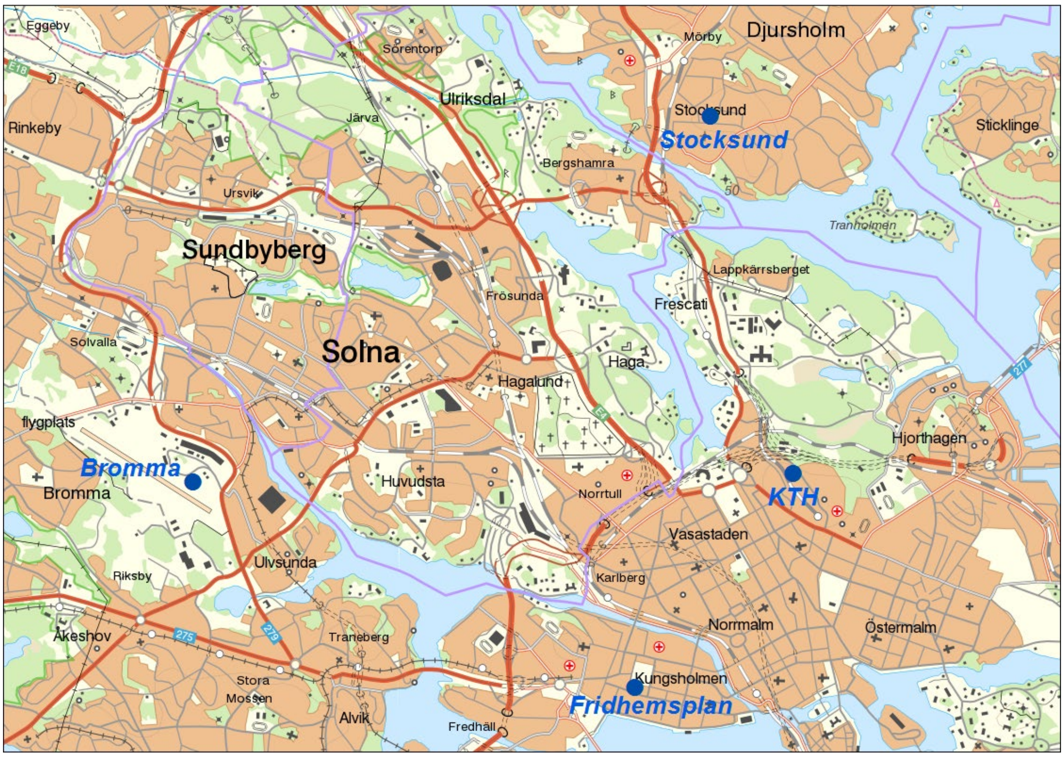


Figure 2.2 Map showing where the global radiation measurements have been sited in Stockholm. Stocksund is the upper one, Bromma to the left, Fridhemsplan the lower one and the present position KTH in the middle to the right. The maximum distance is about 7 km between Bromma – Stocksund and between Bromma – Royal Institute of Technology (KTH). The present site at KTH is located about 3.5 km from Stocksund and 3 km from Fridhemsplan.

One may wonder if there is any significant difference in the radiation climate between these sites. Even though central Stockholm can be reached from the Baltic it is actually far from the open sea. The coastal effect in the radiation climate, seen as a gradient along the Swedish coast, has probably levelled out in central Stockholm.

In Figure 2.2 one can see that central Stockholm is a mixture of buildings, roads, vegetation and open water. The local albedo will probably be relatively low and similar at the sites. There might be some differences during the winter, when there is a substantial snow cover, for the more open and flat location at the airport of Bromma.

Over the long period of measurements of global radiation the city of Stockholm has expanded and so has the number of buildings on expense of fields and forests. But, during the period when the monitoring was located in Stocksund nothing much happened in the local vicinity (within about one km) and the same is true for all locations. So each location has had stable local surroundings during the time monitoring was located there. Therefore, the effects of the changes in location are hard to estimate.

Another factor that one might consider is the pollution caused by heating during mainly the winter-period. In the first half of the series most buildings were heated by wood, gas or charcoal. After the Second World War gas and oil dominated. But starting in the 1950-ties district heating became more and more common replacing gas and oil. The production of district heating may still be based on coal and oil but the emissions were not as dirty as before.

This pollution has of course affected the domes of the pyranometers, but also the pureness of the air itself and the availability of condensation nucleus (clouds) and thus the solar radiation. There are very few notes found where it is clearly stated that this pollution has had effect on the measurements.

If there has been a substantial number of such days where the dome has been severely polluted by soot from nearby chimneys it has probably occurred before 1970. But in this study it is assumed that the operators have cleaned the dome regularly. In the winter half year the problem with frost on the dome is most likely a larger problem. This was the case until ventilator was introduced around the year 1973 in Stockholm.

Table 2.1 Positions of the measuring sites within Stockholm, Sweden.

Site	**Latitude**	**Longitude**	**Height (m)**	**Type of area**
Stocksund	59° 23.2’	18° 03.2’	55	Suburban
Fridhemsplan	59° 20’	18° 02’	43	Urban
Bromma	59° 21’	17° 57’	12	Airport
KTH	59° 21’	18° 04’	30	Suburban

2.3 Instruments

Over the long period of time a number of different instruments have been used. Unfortunately, the old ones do not exist anymore and their characteristics can thus not be examined. All instruments that have been used for measuring the global irradiance are chronologically listed in Table 2.2.

In the early years instruments were used for extended periods. Since 1983 they are regularly replaced by newly calibrated units. In the past the instruments were calibrated at site. Since 1983 the instruments are replaced when the automatic station is visited for service with newly calibrated units.

*Table 2.2 All sites are within Stockholm.*Indicates unknown instrument number. **Probably this number is an internal SMHI number and the instrument is identical to 690225. Some of the series have an overlap in time.*

Site	**Instrument type**	**Number**	**Start**	**Stop**
Stocksund	Ångström	2	1922 July	1931 January
	Ångström	40	1931-02-03	1945-10-08
	Aurén solarimeter		1939 May	1942 Oct sporadic use
Fridhemsplan	Kimball-Eppley	*	1945-10-01	1951-07-23
	MG	635	1951-07-23	1951-07-28
	Kimball-Eppley	*	1951-07-29	1951-10-10 kl.14
	MG	635	1951-10-10 kl. 14	1957-08-09 kl. 9
	MG	982	1957-08-09 kl. 9	1959-03-08
	MG	635	1959-03-09	1960-03-31
	MG	621	1960-04-01	1966-08-29 kl. 10
	K&Z CM2	662560	1966-08-29 kl. 10	1975-05-31
Bromma	K&Z CM5	21875**	1975-06-01	1978-06-30
	K&Z CM5	690225	1978-07-01	1983-12-31
KTH	K&Z CM11	*	1982-09-17	1984-01-31
	K&Z CM11	810252	1984-01-31	1986-02-28
	K&Z CM11	820081	1986-02-28	1988-04-26
	K&Z CM11	850748	1988-04-26	1990-01-13
	K&Z CM11	820139	1990-01-13	1992-11-24
	K&Z CM11	820136	1992-11-24	1994-10-07
	K&Z CM11	850769	1994-10-07	1999-10-19
	K&Z CM11	820135	1999-10-19	2000-08-15
	K&Z CM11	820130	2000-08-15	2003-02-13
	K&Z CM11	820086	2003-02-13	2005-11-22
	K&Z CM11	820072	2005-11-22	2006-08-31
	K&Z CM21	051514	2006-09-01	2010-06-18
	K&Z CM21	051486	2010-06-18	2011-11-09
	K&Z CM21	051485	2011-11-09	2013-04-18
	K&Z CM21	051525	2013-04-18	2014-07-16
	K&Z CM21	051424	2014-07-16	--- >2019

2.4 Radiation scales

A large quality advantage for the data recorded in Stockholm is that there have always been good reference instruments available. The Ångström compensation pyrheliometer was invented by Knut Ångström in the late 19th century and this type of instrument has been used as a reference for the measurements in Stockholm both by Aurén and by SMHI. The old part of the series therefore refers to the Ångström 1905 radiation scale.

Unfortunately, the author has not found any distinct meta-data confirming when the data stopped referring to the Ångström scale and started to apply the Smithsonian scale. Also the date for the transition to the IPS-Stockholm is not well documented, although some notes exist to support the dates that have been used. The time to leave the Ångström scale seems to coincide with the start of using the Kimball-Eppley instrument in late 1945. For a very long period there was no notification which scale was used for the data published in the Yearbook or the monthly summaries published by SMHA/SMHI. And when such information was included starting in late 1956 (Smithsonian scale), it wasn't changed in the following years although the published data referred to IPS-Stockholm starting in January 1957.

The Table 2.3 below is based on the most trustworthy information the author has found. But it cannot be certain that deviations may exist.

A peculiar aspect is that there is a period of eight years when the Smithsonian scale was used for published data. After that it was decided internationally that the IPS 1956 (International Pyrheliometric Scale) should be used starting in January of 1957. However, in Sweden IPS 1956 was not used, instead a scale based on a set of Ångström pyrheliometers was applied. It slightly differs from IPS 1956 and it is here named IPS-Stockholm. This national scale was used by SMHI until the WRR was launched in 1981.

*Table 2.3 Radiation scales that have been used and the correction factor applied to get WRR (World Radiometric Reference). *Note that the IPS-Stockholm differs from the IPS-1956.*

Radiation Scale	**Period in Stockholm data**	**Factor**
Ångström	1922 - 1945 Oct	1.026
Smithsonian	1945 Nov - 1956	0.991
IPS-1956		1.022
IPS-Stockholm *	1957 – 1980	1.011
WRR	1981 -	1.000

2.5 Calibration references and methods

For the absolute calibrations of the pyranometers the shading disc method has been the most common method used. Some details how this was done at least in the late 1950-ties and probably up to 1983 can be found in SMHI (1960). However, during the monitoring at Bromma a reference pyranometer has probably been used.

For the measurements at Stocksund calibrations initially have used the Ångström pyrheliometer Nr 158. There are also some notes mentioning a Michelson bimetallic pyrheliometer, No 129. There are no notes found of calibration frequency or actual data of the calibrations in the early years.

Aurén also constructed a pyrheliometer, Aurén (1935), which seems to have been used frequently during 1936 to 1945. Unfortunately, this instrument has most probably degraded over the years causing a systematic error in a part of the data set; see section 3.1 for more details.

At SMHI-Fridhemsplan from 1945 up to 1975 the most frequently used reference pyrheliometer was the Ångström pyrheliometer Nr. 158. But, also other pyrheliometers have been used such as Ångström Nr. 153, Nr. 171, Nr. 571, and Nr. 585. The documentation found is not always well structured so there might be also other reference instruments used over the years.

During the period at Bromma, 1975-1983 a Kipp and Zonen CM5 (# 690225) pyranometer was used there for the monitoring. The calibration during that period seems to have been a travelling reference pyranometer, probably another CM5 but maybe also an Eppley PSP could have been used sometimes according to notes by Helge Björklund (former technician at SMHI). This shift of calibration method may have caused a systematic difference in the measured data.

Starting with the upgraded national network in 1983 the instruments were usually calibrated at SMHI in Norrköping and then sent to the sites; e.g. KTH. Initially, an Ångström pyrheliometer and the shading disc method were used. But from around 1990 the method of sum of components has been applied.

2.6 Units

The units that has been used for the global irradiation has varied over time as presented in Table 2.4. The reason (as the author was told) to use the slightly strange $mWhcm^{-2}$ was to save 'space'. In the beginning of the computerized era you had to compress and optimize your programs and squeeze the data due to lack of storage capacity. If it was possible to omit a decimal point and store data as integers it was done.

SMHI has not followed the recommendation by WMO to use the SI-unit J (joule) for irradiation, instead watt-hours (Wh) have been used and watt-hours will be used for the final values in this report.

Table 2.4 Units used at SMHI, Sweden, for the global irradiance.

Unit	Period	Factor to get Whm-2
g cal cm^{-2}	1922 – 1970	11.63
mWh cm^{-2}	1971 - 1983	10
Wh m^{-2}	1983 -	1

2.7 Time

It seems that *true solar time* has been used from the beginning up to 1983 (Bromma). In 1983 when the monitoring was automated and moved to KTH Swedish normal time (MET) has been used.

To keep the time setting accurate has really been a problem. But, as long as only daily values were considered the exactness of time setting wasn't crucial. The clock speed should of course not vary too much to have a correct recording of the daily sum under the curve.

However, as hourly values were analyzed from the records one had to decide upon what time interval an hourly value should represent. And also what type of time that should be used. Before 1983 true solar time has been used with time-interval such as 11-12, 12-13, 13-14 etc. The operators should check the time every day and draw a line on the paper roll for confirmation. If the true solar time wasn't correct the paper should be adjusted. Time-corrections could also be applied afterwards in the evaluation process of the paper roll.

By plotting the digitized hourly data along with the solar elevation for a selection of days it can easily be seen by eye that the time hasn't always been adjusted properly. For sunny days the two curves should track each other without any obvious offsets. To correct this afterwards is a Sisyphos work and has thus not been done for this report. There might be periods when the registration intentionally has been operated in local time. If so, it has not been clear from the metadata available. Thus the recommendation is to be very cautious using the hourly data up to 1982.

Starting in 1983 Swedish normal time (MET) has been used. For a couple of years in the 1980-ties the electronic clock used by the automatic station was relatively bad. Time errors of several minutes may have occurred in the 1980-ties. There have also been cases in the first years with power breaks. At the following restarts the clock was zeroed. In these cases the time error could be very large.

2.8 Sunshine duration

Analyzing data series of disputable quality it is always an advantage if there are other parallel measurements to compare with. Even if the other series doesn't measure exactly the same physical quantity there may be some correlation that contains information which can be used for comparison over extended periods.

To find other series of global radiation measured at nearby sites (e.g. Northern Europe) is not easy for the oldest parts of the Stockholm global radiation series. However, there are measurements of sunshine duration recorded in Stockholm. Unfortunately, the available records are not always from the same site. To be able to take the maximum benefit from these records most of the sunshine duration data has been digitized; but not all. The sunshine data has also been checked and sometimes changed when an error is obvious; see examples below.

There are three main applications of the sunshine data. The first one, as mentioned, is to compare with the global radiation to find obvious questionable data (both quantities can be in error). The second one is to use the sunshine data in the correction procedures for directional errors of the pyranometers, as will be described later. The third application is to use sunshine duration data to fill in gaps in the records of global radiation. This has partly already been done by the primary evaluators in the past. As the recording equipment failed now and then the sunshine duration was often used as input to interpolate missing hours and days to get a complete monthly dataset.

More information on how sunshine duration data has been corrected can be found in Appendix 3. There is also a Table A3:1 with all corrected monthly values of sunshine duration for Stockholm late 1904 to 2018.

Table 2.5 Series of sunshine duration used in this study. The columns give site, instrument, period and available digitized data. Axel Hamberg's instrument is a Jordan type of photographic sunshine recorder, mostly used is the Campbell-Stokes sunshine recorder (C-S). *After the automation of the network the sunshine duration was measured by a pyrheliometer* (*Eppley-NIP). But when the suntracker was removed we had to replace the pyrheliometer by static instrument CSD3 from Kipp and Zonen.*

Site	**Instrument**	**Start**	**Stop**	**Data**	**Important missing periods**
Skansen	C-S	1905-	1916	month	
Vanadislunden	Hamberg	1908-	1926	daily	
Vanadislunden	C-S			daily	
Vanadislunden	C-S	1942-11-01	1951-10-30	hourly	Jan-May 1944, Jan-Aug 1945
Fridhemsplan	C-S	1951-11-01	1975-04-30	hourly	
Bromma	C-S	1975-05-01	1983-12-31	hourly	
KTH	Eppley pyrh.	1983-01-01	2006-08-31	hourly	
KTH	K&Z CSD3	2006-03-01	ongoing	hourly	July 1998

Plotting daily values of sunshine duration versus the corresponding global radiation for the same month sometimes revealed that one of the quantities was in error. In many cases the cause was that the sunshine duration was shifted one day, because heliograms from the sunshine recorder are easily mixed up. This error could easily be corrected by adjusting the days by one step. If one was in doubt which quantity should be shifted one could check using precipitation and or cloud observations to get the best correspondence.

Another frequent error (noted as outliers in the plot) was that rime on the heliograph caused an almost zero sunshine duration during sunny days whilst the global radiation value could be large although also this instrument had rime on the dome. To correct these days was trickier and sometimes even hopeless. The sunshine duration should most probably be increased and the global radiation should in some cases be reduced but for other decreased. This type of problem was strongly reduced when a heater was introduced for the heliograph (from 8.40 true solar time on 3rd October 1970[1]) and a fan blowing slightly heated air over the dome of the pyranometer (around 1973[2]).

Regarding the sunshine duration it is most useful to have hourly values, but even daily values can be useful for quality controls. Unfortunately, for large parts of the earliest years in the Stockholm series only monthly values of sunshine exist.

[1] Archive box D4 HI:1

[2] Personal communication Sverker Magnusson

2.9 Cloudiness

At the meteorological station Stockholm-Observatoriekullen the cloud amount has been observed three times a day since the start 1756, available from Bolin Centre (https://bolin.su.se/data/stockholm/observed_cloud_amount.php).

The observation procedures and reporting-scales have varied and the quality is highly questionable. It is clearly stated on the web page that these data shouldn't be used for trend studies. Despite these drawbacks the data has been used in this study because there are so few other supporting data.

2.10 Model data from CERA

A few comparisons were also made versus 20th-Century Reanalysis, Version 2c from NOAA and CERA-20C, Poli et al. (2016), from ECMWF (≈125 km, 1901-2010) modelled global radiation. Relatively large differences were observed and here is only one figure presented.

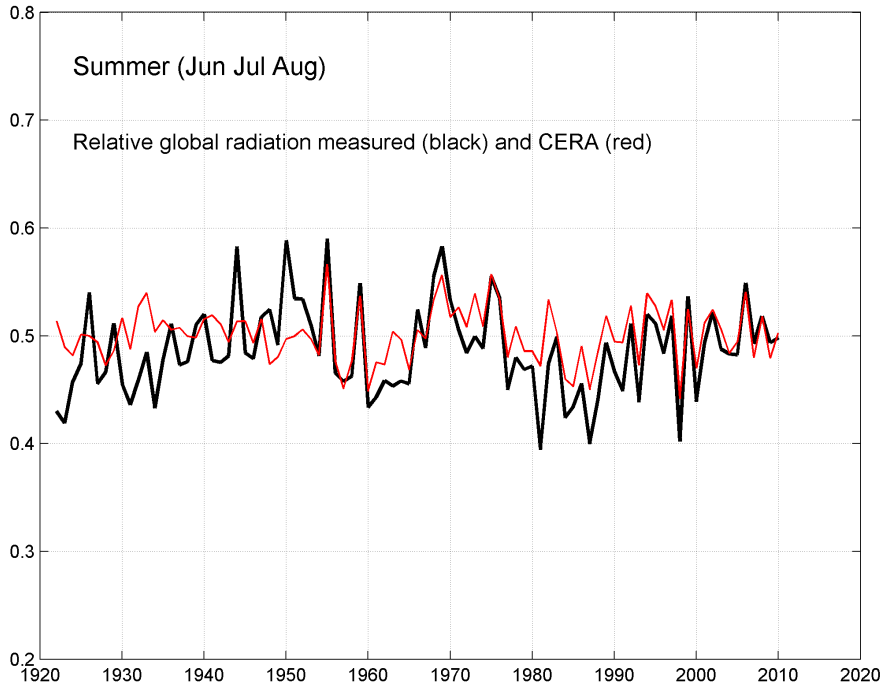


Figure 2.3 The relative global radiation (G/G_{ex}) for the summer (Jun, Jul, Aug) is plotted for the period 1922 to 2010. Observed data for Stockholm (black) and modelled CERA-20C from ECMWF (red).

At the end of the series data seems to agree better and better. The early part, before about 1950 the CERA data seems to be less variable than the observed. Some smoothing in the modelled data compared to the measured could be expected as it is modelled for rather large areas (≈ 125*125 km^2).

3 Data retrieval and processing

The following steps has been applied

- Digitizing raw data (if available) otherwise irradiance values
- List applied calibration constants
- If possible find out how and when they were done
- Find out which unit and radiations scale that has been used
- Check that the digitizing was done correct
- Find out if data has been interpolated, corrected
- List instruments and periods when they were used
- Try to find instrument characteristics
- If possible correct for systematic errors caused by instrument characteristics
- Digitizing ancillary data; sunshine duration, precipitable water, air-temperature
- Compute extraterrestrial global irradiation and length of the day
- Uncertainty estimate

3.1 Early period 1922 to 1945

The recording using the Ångström pyranometers Nr. 2 and Nr 40, in the early period 1922-1945, was done at Stocksund a suburb of Stockholm. The recording was done on photographic plates, described by Ångström (1928) and Aurén (1930).

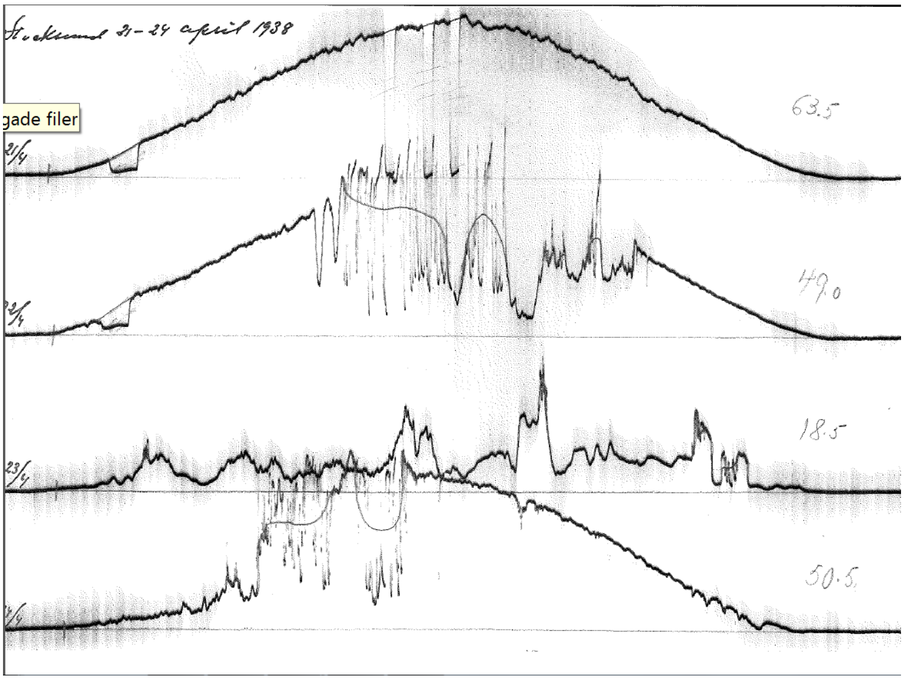
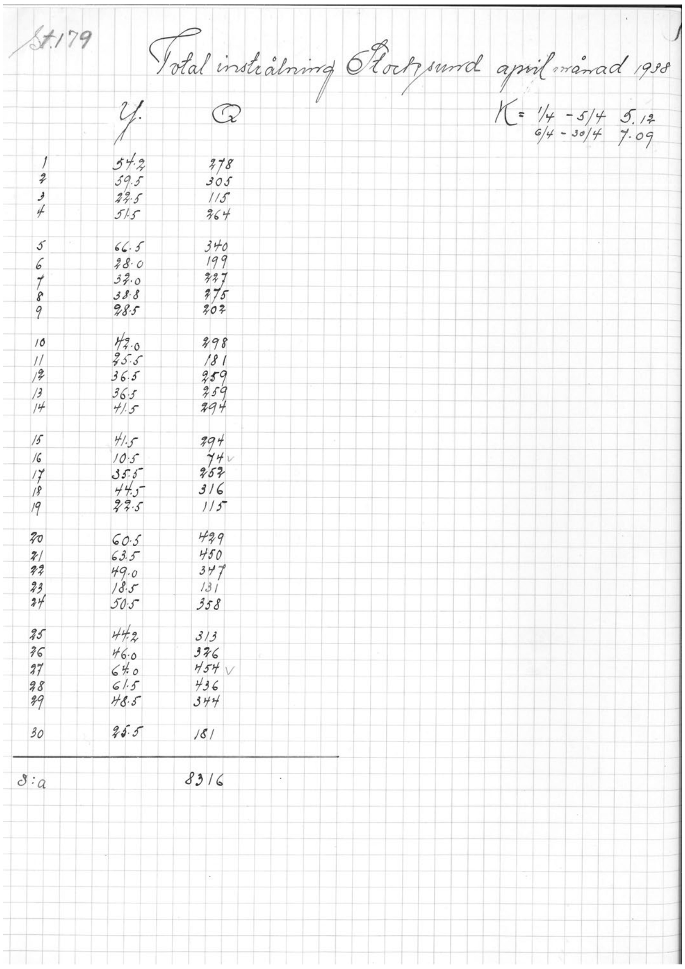


Figure 3.1 A photo found in the archive of SMHI showing the registration of four days 21-24 April 1938. Note the averaging during periods with strong and rapid variations. Some dips are interpolated e.g. in the top one there is an obscuring object causing a false dip to the left and during the day there has probably been a calibration using a shading disc at three occasions.

The signal from the instrument deflected a mirror-galvanometer. A reflection from a lamp was directed towards a slit in front of a camera. A photographic plate moved using clockwork. On the photographic plate a curve was registered. Unfortunately, these original records are no longer available for re-examination. Using a curve following device (planimeter) the integral of the daily curve was measured.

The rawest piece of information for the oldest period that has been found in the archive of SMHI is the handwritten daily values of the integral value. Together with the instrument constant for each month this constitutes the rawest available information. Unfortunately, not all daily values have been found in the archive. In those cases the irradiation values published in the monthly and yearly bulletins of SMHA have been used.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Total instrålning Stocksund april månad 1938

K = 1/4 - 5/4 5.12
6/4 - 30/4 7.09

	y.	Q
1	54.2	278
2	59.5	305
3	22.5	115
4	51.5	264
5	66.5	340
6	28.0	199
7	32.0	227
8	38.8	275
9	28.5	202
10	42.0	298
11	25.5	181
12	36.5	259
13	36.5	259
14	41.5	294
15	41.5	294
16	10.5	74 v
17	35.5	252
18	44.5	316
19	22.5	115
20	60.5	429
21	63.5	450
22	49.0	347
23	18.5	131
24	50.5	358
25	44.2	313
26	46.0	326
27	64.0	454 v
28	61.5	436
29	48.5	344
30	25.5	181
S:a		8316

Figure 3.2 Example of daily values April 1938. Day, evaluated area (y) and after application of the calibration factor (K) the daily irradiation (Q). The evaluated values from Figure 3.1 can be found here.

In Ångström (1928) hourly values of global irradiation are published for the period April 1926 to August 1927. These hourly values have been used to study the effect of cosine correction for the Ångström pyranometer. A relation between the correction and the relative global radiation for daily values was established. This relation was then applied to all data measured by the Ångström and Aurén pyranometers. It is assumed that this would reduce the effect of the improper cosine response of the old instruments on the final data. It is fully understood that this method is far from perfect but hopefully the systematic error will be somewhat reduced.

Ångström (1928) used sunshine duration to fill in some gaps in the data to have complete monthly totals; a method that probably has been applied many times over the years. This method has also been used in this report. It is unfortunate that for extended periods only monthly data of sunshine duration are available for Stockholm before the 1940-ties. This hinders a more detailed quality control of the oldest data. Available cloud observations helps but it is far from the best indicator of solar radiation.

The operation of the instruments was performed by Aurén. He was deeply interested in measurements of radiation (UV and illumination). He also developed some radiation instruments. One of these the Aurén solarimeter was used to fill in gaps (1938-1942) when the Ångström pyranometer failed.

In the process of digitizing and retrieving the rawest possible data errors have been detected by checking daily and monthly sums. The most common error found is after multiplying the integral value by the instrument constant the value is rounded to the nearest whole number. Sometimes this is done systematically in one direction or sometimes the combination of the two numbers gives a systematic higher or lower end result.

For some years and months the individual hourly values are rounded, then summed to daily values and to the monthly value. This procedure will produce unnecessary errors of the order 1%. This has been observed for many months up to the 1960-ties.

Or more unfortunate the product is miscalculated. This occurred maybe once a year causing a large error in the daily value and a significant error in the monthly value as well.

As the author scrutinized the values there was also found some values that had been digitized in error. These were easily corrected comparing with the original documents. Another thing that was noted during the control of the digitized data was that the decimal value of the integral value often was either zero or five; approximately 95% of all daily values. This means that roughly the effective resolution was about 5 (=0.5*10) gcal cm^{-2} in the daily values. The actual last digit in the daily value could of course vary depending on the applied constant each month.

In Ångström (1928) p.13 there is a simple estimate of a probable error in the data. In his interpretation he states that there are three sources of error; the calibration, the time as given by the rotation of the recording cylinder holding the photographic plate and the uncertainty of the area evaluated using a planimeter. For many daily values of global radiation his estimate of the relative error (±0.07) is probably of the correct order. However, in extrapolating this uncertainty to monthly and yearly values Ångström is probably too optimistic. Hidden in the calibration are instrument dependent errors which are systematic and dependent on spectral composition of the solar radiation, the angle of incidence of the radiation etc.

His estimate of the uncertainty emerging from the use of the planimeter is of great interest as this procedure cannot easily be reproduced now. This because the original records are lost and so is the planimeter.

In the beginning of this work the author thought that an Ångström pyrheliometer had been used at Stocksund on a regular basis to calibrate the pyranometer from the start to the end of the monitoring at that site. However, this seems not to have been the case.

An important piece of information was found on page 7 in Aurén (1944). It says: "The constant of the pyrheliometer used for checking the recordings at Stocksund has proved to remain constant over the 8 years it has been in use, but it is somewhat too low, and as, furthermore, it will be desirable that the results be expressed in the now fairly commonly used »Smithsonian scale revised 1913», the values in these tables should be multiplied by the factor 1.086." The mentioning of 8 years is interesting because it gives an indication that something happened in the mid 1930-ties. According to a paper Aurén (1935) had constructed his own pyrheliometer. A hypothesis can then be that the Stocksund pyranometer was calibrated using this new pyrheliometer by Aurén starting in mid-1930-ties up to the end of the Stocksund-series in 1945. There is some evidence for this; based on the Aurén letters which he mailed together with the recordings every month; found in the archive of SMHI. They cover a period from March 1936 up to November 1945. Unfortunately, the raw-recordings have not been found.

If we remove the difference between the Ångström and Smithsonian scales from this factor 1.05 will remain. The tables that are mentioned refer to an earlier publication Aurén (1939) and those encompass data from pre 1937.

Based on this information values from Stocksund have to be increased by 5% at least for the years 1936 to 1945.

But, in late 1943 or early 1944 Aurén probably was aware of the pyrheliometer calibration error. Therefore, a guess is that the values of 1944 and 1945 are not affected by this error.

Aurén's letters attached to the data he sent to SMHI usually only contained a brief text telling how many calibrations he had done and the average instrument constant he deduced from these observations. But, in the letter dated 6 June 1944 he mentioned that the meteorologist Olsson had made a calibration on the 7th of May with the SMHA instrument and according to the Ångström scale it was 9.17. Also the next letter dated 3rd July 1944 stated that the calibrations during June were made by the SMHA instrument.

The conclusion of this is that data reported and published at least from May 1944 are not as low as the previous years, when they were only calibrated using the Aurén pyrheliometer.

So, what about the years before 1936? In Ångström (1928) there is no information how frequent calibrations of the pyranometer were done. And there is no correspondence with Aurén found in the archive before 1936. So, one can only make assumptions that Aurén borrowed an Ångström pyrheliometer now and then and made calibrations. There is also no complete documentation of the applied constant for the pyranometer. However, there are relatively many monthly constant values prior to 1936 showing that the applied constant has varied over the year and in between years. Therefore, it is a fair guess to assume that there have been a number of calibrations done in the years 1922 up to 1936.

3.2 Period 1945 to 1983

The recording of global radiation on the roof of SMHI (before 1945 SMHA) started in October 1945 at Fridhemsplan in Stockholm using a Kimball pyranometer. Also starting at the same time was the evaluation of hourly values that can be found in the archive. This type of handwritten monthly protocols was used up to 1983. The data from these protocols have been digitized; mainly by students working in summer time. Another thing that was changed starting with the Kimball pyranometer was the use of the Smithsonian radiation scale.

Occasionally, there were some gaps, missing protocols or interruption in the measurements, due to stop in the monitoring. Some of these could be filled in by re-analyzing the original records (by the author) that were available on strip charts (paper rolls) found in the archive. Despite this there are still some gaps to consider. The longest gap lasted from January to July in 1948 due to instrument failure and repair. The method used to fill this and similar gaps will be described later.

Two important things affecting this study happened in the late 1950-ties. It was internationally decided to use a new radiation scale, called IPS-1956. However, in Sweden this wasn't exactly the case. The reason why is not clear to the author, but starting in 1957 Swedish solar radiation data refer to what here will be called IPS-1956-Stockholm, which differ by 1.1 % from the internationally recommended IPS-1956.

The other thing that started in 1957 was the International Geophysical Year (IGY) 1957-1958 and that the SMHI increased the national network in Sweden from one station to ten. This apparently boosted the interest for global radiation measurements for a couple of years at SMHI, which can be seen in calibration activities and a number of yearly publications.

In the 1970-ties several governmental bodies were relocated from Stockholm to other parts of Sweden. SMHI had to move to Norrköping. Therefore, the measurements of global radiation and sunshine duration in Stockholm had to be moved from Fridhemsplan to the airport of Bromma.

The oldest original records, analog print-out in form of strip charts rolls, which can be found in the archive of SMHI is from January 1953 looking like the example from 1977 in Figure 3.4. Every second minute a dot was printed on the paper representing the voltage from the potentiometer connected to the instrument. A clock-work slowly moved the paper about 20 mm per hour. After each month these rolls were manually analyzed (connecting the dots) and estimating the average over each hour. On the strip chart roll the distance from a zero-line to the "average of the hour" was measured using a special ruler, Figure 3.3. These rulers (not always linear) varied depending on the acquisition system used.

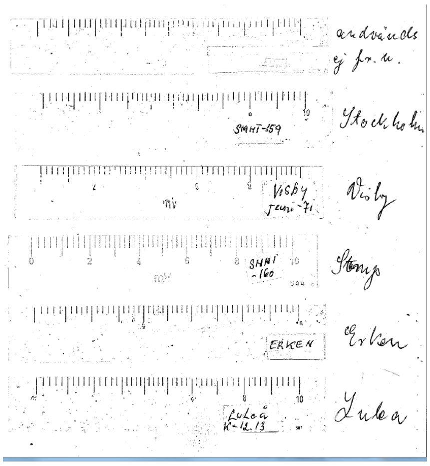

Figure 3.3 Examples of rulers used in 1973.

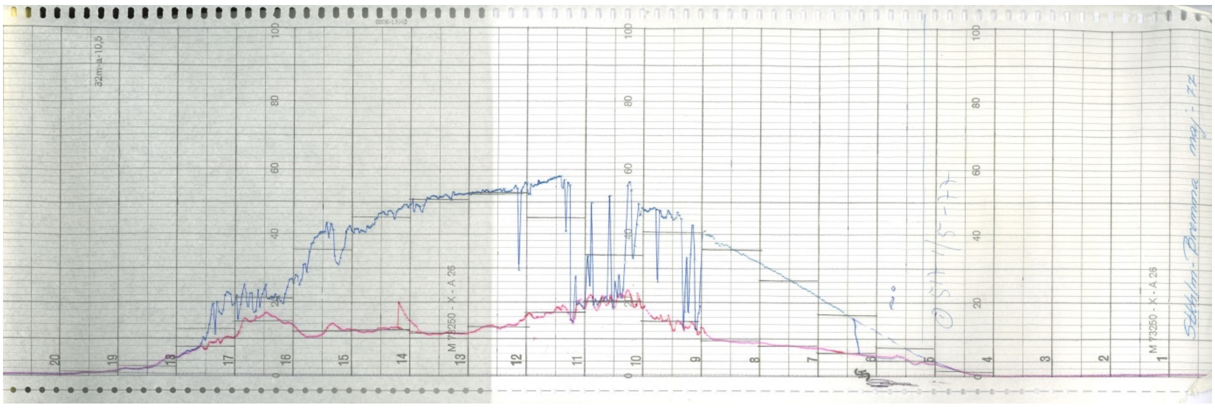

Figure 3.4 Example of a strip chart registration for the 1st of May 1977 for Stockholm-Bromma. The paper was supposed to move according to the time indicated on the paper. Every day the operator should draw a line and write the date and the true solar time on the strip chart; in this case 5:11. Every second minute a red dot (diffuse solar radiation) was punched on the paper and a minute later a blue dot (global radiation). To evaluate the data one had to draw by hand a line connecting all small blue dots. Then by eye estimate an hourly average in form of a horizontal line. Finally, one had to measure the distance from a zero line to the horizontal line using a special ruler. This ruler varied from station to station. It was graded according to the recording system used, so the scale of the ruler mostly differed slightly from the scale of the paper roll.

These subjectively integrated hourly raw-values (scale-units) were put into the monthly forms, Figure 3.4. To find the irradiation of the hourly values the scale-units had to be multiplied by a factor; the so called instrument-constant. This factor was usually determined by a shading disk calibration.

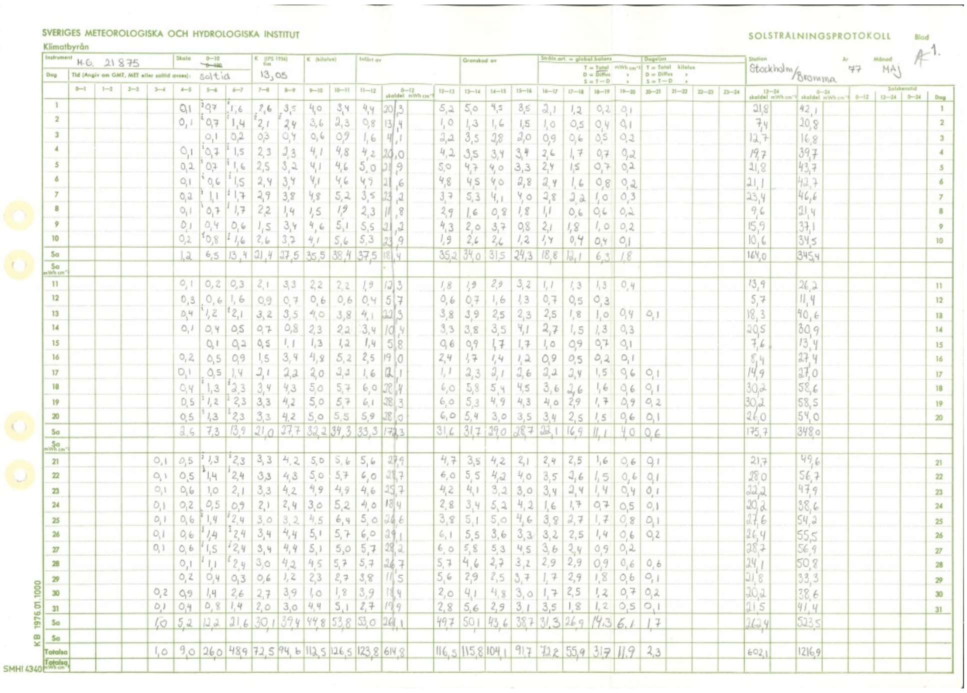

Figure 3.5 Evaluating a strip chart gives one dimension-less number (scale units) per hour. These hourly numbers were summed into rows (daily value) and columns and finally to a monthly sum (lower right). To get the irradiation these numbers have to be multiplied by the instrument constant, which in this example is given in the upper left as 13.05 (mWhcm^{-2} per scale unit).

Somewhere around 1973 (pers. communication Sverker Magnusson former technician at SMHI) the pyranometers in Stockholm and the entire network became ventilated. A fan blowing slightly heated air over the dome prevented frost and rime on the dome. But, it was also relatively effective to remove raindrops and snow (if not too much).

The calibration factor used at Bromma was not changed much over the years. The two last changes in March 1980 and January 1981 were caused by a change in the strip recorder respectively the introduction of WRR (World Radiometric Reference).

3.3 Automated recording

3.3.1 Period 1983 to 2007

When the site of the monitoring changed location from Bromma to KTH (Royal Institute of Technology) starting in 1983 there was an overlap operation of the “old” station at Bromma-Stockholm and a “new” one at Stockholm-KTH. There were also some other changes that occurred at the same time that will be discussed below.

However, evaluating the data for one year of overlap (1983) it was noted that there was a relatively large difference for all stations in the network. For Stockholm some of the difference might be attributed to the change of site. But a change in location could not explain the detected difference for most of the other sites. The overall pattern in the difference was similar. The “old-network” gave about 5% higher values compared to the “new” in the summer and an increasing difference approaching the winter months. The hypothesis for the seasonal behavior of the difference was that the instrument type changed from Kipp and Zonen CM5 to CM11; instruments with difference in their directional (cosine and azimuth), temperature responsivity and the offset. Correcting for these factors for the overlap year 1983 in Stockholm remove the seasonal behavior. However, there is still an overall systematic difference. The assumption is that this could be explained by a change in the calibration procedure.

Since 1983 data has been collected automatically as hourly values using MET hourly intervals. Prior to that date the recording devices were adjusted to track TST (true solar time). Both these systems were not perfect and adjustments of the clock and the recording device had to be done now and then. Therefore, one cannot be sure if the hourly values are properly synchronized to the time interval they are intended to represent.

During the 1990-ties the clocks of the automatic stations became better and the time error was not a problem anymore. If daily values are considered this effect disappears.

It seems that TST has been used for all data in the past as far it has been possible to check. But, it cannot be 100% confirmed there might some periods when local time has been used instead.

In the original protocol for August 1951 there is a brief note on top of the paper. "*fr.o.m. aug 51 anv. soltid och avläses på halvtimmen*" underlined by a red pen. An interpretation of this could be starting in August 1951 the reading from the registrations should be done in true solar time.

The collection and storage of data from the automatic stations were not raw data (e.g. as voltage values). The pyranometer sensor was frequently sampled; about 1 Hz. In the processor (computer) of the automatic station the calibration constant was applied to 6-minute average values. These irradiation values were stored locally and once an hour the station was contacted using a telephone-line to retrieve the ten 6-minute averages to a central computer at SMHI in Norrköping. The ten collected global irradiation 6-minute values had a precision (resolution) of 1 Whm^{-2} and summing the ten values for each hour and divide by ten the hourly global radiation was stored in the database with one decimal in Whm^{-2}.

3.3.2 After the upgrade in 2006 - 2007

The automatic technology introduced in 1983 became old and in 2007 the automatic solar radiation network of SMHI was upgraded. The old technique and the instruments were replaced. The Kipp & Zonen CM11 were replaced by CM 21. From 2007 the raw data are collected as averages for every minute of the measured voltage from the pyranometer. The calibration constant is applied afterwards. Global irradiation is usually stored with a resolution of $0.01 Whm^{-2}$.

An overlap period for more than a year was studied by Carlund (2011). The agreement between the new measurements of global irradiance and the pre-2008 were relatively good. However, Carlund (2011) noticed a small dependence on solar elevation. The summer values for the old instruments (CM11) were in general a few per mille too low. Having a low sun in the winter months gave slightly higher values for the CM11 compared to the new CM21's.

4 Correction for instrument characteristics

Unfortunately, instruments intended to measure the global irradiance suffer from several drawbacks. For example the response of the unit is dependent of the ambient temperature or on the angle of incidence of the incoming radiation. The ones giving the strongest influence are thoroughly studied for modern instrument, but that may not be the case for older types of radiometers.

Here the approach has been to list the typical sources of errors caused by the instrument and see if it can be corrected for. If so, a simple parameterization (algorithm) has been developed, based on available test-data, and applied. The specific instruments used in Stockholm have not been characterized individually. But there is information published of the typical behavior of the type of instrument used. This can be used to make a correction that hopefully reduces the systematic features that some of the errors produce. An example: If the instrument is calibrated at temperatures close to 15°C measurements in the winter (often at temperatures below zero) will systematically deviate from those made in the summer.

<u>The general assumption in this report is that systematic errors can be reduced by the application of even rough corrections</u>.

Of course there will (probably often) remain some systematic error after the correction has been applied. But, it is plausible that the random errors will dominate in most cases. In the following sections references to instrument characteristics and their effect on the measurements will be presented and discussed. The exact algorithms applied are given in the Matlab-code used which is printed in Appendix 1.

The following characteristics of the pyranometers have been scrutinized and if possible corrected for.

- Electrical and thermal offset
- Non-linearity
- Temperature dependence
- Directional responsivity (cosine and azimuth)
- *Calibration ....*

Other instrument characteristics that may affect the data like time-constant, variation in spectral responsivity and eventual tilt of the instruments will be discussed. But, they are not included in the correction algorithms.

There are of course other sources of uncertainty, which have been dealt with in various ways, which partly is described in other sections of the report. Calibration values that have been applied, usually one value per month, have been scrutinized and if errors have been detected changes are made.

Some clearly erroneous single hourly values have been adjusted. Example on that is when the sun was obscured by a nearby object or periods when frost or snow has covered the dome. For the years of manual processing some evaluators have done this correction others not. So if detected these corrections have been done processing the raw data.

For the early types of instruments some information was published in Köhler (1937) and Johnson and Olsson (1944). In the early 1980-ties there was an IEA-project that made a number of characterizations of pyranometers including the Kipp & Zonen CM5 and CM10/11, IEA (1984) and Wardle and McKay (1984).

- overcast-correction
- clear sky correction
- interpolation using sunshine duration (hourly)
- How to handle if only daily data available

The calibrations of the pyranometers were done more or less frequent over the years. Sometimes using a reference pyranometer, but mostly the shading disk method has been used. That is the pyranometer was shaded for a short period; mostly 10-30 minutes. At the same period the direct normal irradiance was measured by an Ångström pyrheliometer. The global irradiance lost by the shading should correspond to the horizontal component of the direct.

As the Ångström pyrheliometers used at SMHI were well calibrated and operated by skilled personal such a calibration should produce an accurate estimate of the pyranometer responsivity. The found calibration factor was often applied to long period of time. However, one must be aware of that the pyranometer responsivity varies depending of e.g. solar elevation and temperature.

The influence on the measured global irradiance of these effects can be roughly estimated by correction for actual temperature and solar elevation compared to the temperature and the solar elevation that existed during the calibration. Sometimes these values are found in the archive but not always. Therefore, it was tested for a brief period of time (1968), where the calibration shifted several times, how large the difference in global irradiance would be if one uses the actual temperature values and solar elevations of if one uses 20˚C and 40˚ solar elevations as default values. In the monthly values the difference was only a few per mille during the summer and around half a percent higher during the winter. It would be great if the influence from this effect could be minimized, but it is also comforting that the eventual error is small in particular for the summer-half-year where most of the solar irradiation resides.

4.1 Ångström's pyranometers

The Ångström pyranometer and recording method used in the 1920-ties is described by Ångström (1928). The method of recording is also nicely described by Aurén (1947) who was responsible for the monitoring in Stocksund on the roof of his villa.

Aurén (1947) is also discussing some measuring problems such as moisture in the instrument, calibration method dependency on clear skies, variable spectral responsivity of different instruments, and uncertainty in the determination of the raw-value from the photographic registration. Aurén was also aware of the change in the heat-balance (i.e. change in the offset) as well as the influence from the solar aureole when making a shading disc calibration.

Unfortunately, no test of the temperature dependence or the linearity of the Ångström instrument has been found. However, there is a discussion on the spectral dependency as well as a cosine characterization in Köhler (1937). In Schmidt (1929) one can find a graph showing the solar elevation dependency of the instrument constant reflecting the cosine error. If one looks closely into that graph one can suspect there is an azimuthal dependency as well. This is no surprise as the instrument sensor consists of parallel black and white strips.

Also in the paper of Hasché (1933) one can find some data on the characteristics of Ångström pyranometer (with flint-glass). Cosine and spectral dependency is discussed and also an eventual temperature dependency. There is a brief comment that there is no temperature dependency of the c-value (instrument constant) at the bottom of page 27.

In the beginning the instrument (Å Nr.2) was equipped with a flint-glass dome. But, according to notes found in the SMHI-archive it was replaced by an instrument with an opalescent glass milk-glass dome (Å Nr. 40, called Ångström type 1930) starting 3rd February 1931. According to Aurén (1939) p.7 the pyranometer equipped with milk-glass was introduced in the year 1930 at Stocksund, which almost is in line with the previous notes.

The milk-glass version was probably used until the monitoring stopped at the Stocksund site. There is a support for this assumption in Johnson and Olsson (1944) p.17 for the period 1941-1942. In this paper it is also said that the pyranometer is calibrated versus the Uppsala pyrheliometer.

A cosine characterization of the Ångström-pyranometer with flint-glass (nr. 37) and two with milk-glass (nr. 37 and nr. 44) was published by Köhler (1937) pp.37-38. Also see the discussion on p. 75. Therefore, it is most likely that one cosine response is valid up to January 1930 and another one for the following years for the measurements recorded at Stocksund.

Also Lindholm (1958) (at the bottom of p. 296) says that Aurén used milk-glass for the pyranometer measurements in Stocksund. He also comment on the difference in average global radiation between the measurements made in the late 1940 up to mid 1950-ties and the apparently lower values recorded at Stocksund up to 1945. He refers to the work of Rodskjer (1955) and concludes that the determination of the responsivity using the shading disk method on the milk-glass dome Ångström pyranometer would give an instrument constant that is 10 to 15% too low. But, the early period, 1922-1930, was not affected by this eventual problem.

The study of Rodskjer (1955) claims that there is a spectral dependency in the milk-glass that gives instrument responsivity that differs with solar elevation and also between clear and cloudy skies. Rodskjer says in the conclusions that a higher instrument constant should be used for overcast skies compared to one deduced from a clear sky calibration.

More than 70 years after these differences occurred it is hard to find out what really was the cause and how to correct for eventual effects as sufficient data is no longer available. At the time Johnson and Olsson (1944) reported that an intercomparison between monthly values between the Stocksund measurements by the Ångström pyranometer and a Kimball-Eppley pyranometer at SMHA from November 1941 to October 1942 showed a good agreement during the summer. Based on this, one may conclude that the winter values didn't, but this may not be true. The reason might be that winter values are strongly affected by snow and frost deposits.

Table 4.1 Yearly correction factor, due to assumed changing response of the reference pyrheliometer used by Aurén 1937-1945, which has been applied on the observed data.

Year	Correction factor
1937	**1.05**
1938	**1.08**
1939	**1.07**
1940	**1.06**
1941	**1.06**
1942	**1.05**
1943	**1.05**

The discussion at the end of section 3.1 in this report on the calibration of the Ångström #40 instrument concluded that Aurén's calibration probably have been offset by about 5% for the period 1936 to 1944; this because of the pyrheliometer reference used by Aurén.

Comparing the observed values for relatively cloud-free days versus the extraterrestrial radiation indicates that the clear day values are too low for this period. Assuming that this depend on a gradual change of the responsivity of the Aurén pyrheliometer, the yearly corrections presented in Table 4.1 have been applied to the observed values of global radiation.

An even larger correction factor (**0.85**) had to be applied for the two last years with the Ångström pyranometer 1944 and 1945 at Stocksund. The clear sky daily values were far too large. It is unclear why these extreme values occurred. At that time there was another pyranometer available at SMHA so this aberration should have been detected. The faulty calibration of the reference pyrheliometer was noted and corrected in the data from May 1944 according to the documentation found in the archive. At that time it seems that the use of the Smithsonian radiation scale was discussed at the institute and that scale was used for the new Kimball pyranometer starting in October 1945. But, any mix-up of the Ångström (1.026) and Smithsonian (0.991) radiation scales should not give such a large deviation.

In conclusion the data recorded by the Ångström pyranometers have been roughly corrected for the cosine error. Over the years the calibration constant of the instruments has been changed almost every month, in most cases based on actual calibrations versus a pyrheliometer. Thus, the effect of the improper cosine response and of eventual temperature dependence will be included in the monthly calibration constant. To complicate this further the data acquisition system includes a resistance that now and then is changed to get a suitable signal. Therefore one cannot easily study these effects by tracking the variation of the constant for example over the year.

After the simple cosine correction had been applied and some obvious outliers had been removed daily data have been compared to the extraterrestrial radiation. Filtering for days with relatively low cloudiness one can see that the period 1936-1944 probably gives too low values. And that the last years are too high.

4.2 Aurén’s solarimeter

Another type of instrument, the Aurén solarimeter, was used in the series to fill in missing data during 1938 to 1942. Usually, only a few days now and then, but in October 1938 and in May 1939 most data is recorded by the solarimeter. The directional response (cosine) of this instrument was studied by Rodskjer (1955). However, the number of days filled in is few in relation to the number of Ångström pyranometer days. Aurén has calibrated both instruments so it is plausible that they give similar results. The Aurén solarimeter days has thus been treated as they were measured by the Ångström pyranometer.

4.3 Kimball-Eppley pyranometer

Starting 1st October 1945 the monitoring in Stockholm moved from Stocksund to SMHI at Fridhemsplan. At the same time the instrument changed from the Ångström to the Kimball-Eppley pyranometer, which was used up to September 1951.

In the Yearbooks of SMHI the instrument is named the Kimball pyranometer. The author hasn’t found any pictures or documentation that can verify if this was what at that time also was called the Eppley 180˚ pyrheliometer (although it is a pyranometer). For the specific unit there is no characteristic found in any publication or document; not even the instrument number. However, it is most likely this is the case.

One Kimball Eppley pyranometer was briefly tested by Aurén (1947) at least in 1936. According to his description it probably was an Eppley 180˚ pyrheliometer. It’s not impossible that it was the same unit used by Köhler (1937) for his measurements in 1934 and 1935. Unfortunately, the instrument number (198) is only presented by Köhler (1937).

In literature the characteristics of the Kimball-Eppley instrument type can be found; e.g. MacDonald (1951). From this paper a cosine and temperature dependence of a number of units can be found and an average can be deduced and applied on the hourly data.

Citing from Duffie and Beckman (2013) page 48. *"The Eppley 180 pyranometer was the most common instrument in the United States. It used a detector consisting of two concentric silver rings; the outer ring was coated with magnesium oxide, which has a high reflectance for radiation in the solar energy spectrum, and the inner ring was coated with Parson's black, which has a very high absorptance for solar radiation. The temperature difference between these rings was detected by a thermopile and was a measure of absorbed solar radiation. The circular symmetry of the detector minimized the effects of the surface azimuth angle on instrument response. The detector assembly was placed in a nearly spherical glass bulb, which has a transmittance greater than 0.90 over most of the solar radiation spectrum, and the instrument response was nearly independent of wavelength except at the extremes of the spectrum. The response of this Eppley was dependent on ambient temperature, with sensitivity decreasing by 0.05 to 0.15%/ C (Coulson, 1975); much of the published data taken with these instruments was not corrected for temperature variations. It is possible to add temperature compensation to the external circuit and remove this source of error. It is estimated that carefully used Eppley's of this type could produce data with less than 5% errors but that errors of twice this could be expected from poorly maintained instruments. The theory of this instrument has been carefully studied by MacDonald (1951). The Eppley 180 pyranometer is no longer manufactured and has been replaced by other instruments."*

Based on the information available the data from the Kimball-Eppley have been roughly corrected for temperature and cosine under the assumption that the systematic errors are reduced in the corrected data. The applied corrections can be found in Appendix 1.

4.4 Kipp and Zonen CM2 / CM3

In the annals of SMHI there isn't much information on the characteristics of these old instruments to find. Therefore, the author contacted Kipp and Zonen and got in touch with the former employee of the company; Leo van Wely, who sent results where this type of instruments had been tested. He also made a comment in one of the emails that they are relatively similar to the later type CM5; which has been extensively tested over the years; see next section; and this seems to be confirmed by the papers he sent. The applied corrections for these instrument used in Stockholm are thus similar to the CM5 units; for details see Appendix 1.

4.5 Kipp and Zonen CM5

Characteristics of the directional responsivity (cosine and azimuth) for K&Z CM5 and CM10/11 are published in IEA (1984) and based on these data it is parameterized by the author.

Depending on laboratory some differences in the results can be seen. For the Kipp and Zonen CM5 there is a considerable directional responsivity in both cosine and azimuth. As we don't know the characteristics of the units used and also exactly how the old instruments were mounted an idealized cosine and azimuth-response has to be applied for the correction. This is an example of how lacking metadata prevents a proper application of a correction. However, Lars Dahlgren, who was responsible for the solar radiation network from 1977, was always very careful regarding the positioning of the CM5-instruments. They should always have the cable in the direction north.

The dependence of the responsivity on the level of the irradiance (linearity) and on temperature is well described in the IEA (1984) report. The influence from offset is substantial. It will be discussed in a later section. The applied correction algorithms can be found in Appendix 1.

4.6 Kipp and Zonen CM10/11

The characteristics of the Kipp and Zonen CM10/11 were also tested by IEA (1984). Also here there are some differences between laboratories but in general this instrument has small deviations compared to accurate and precise references. So the applied corrections will be relatively small compared to older instrument types.

As the characteristics of the individual CM10/11-instruments used at Stockholm are not known and that the eventual corrections are small in this context there has not been any correction done.

4.7 Kipp and Zonen CM21

The latest instrument type from Kipp and Zonen CM21 has improved and is very close to our main reference for global irradiance. No corrections have been applied for these data.

4.8 Various corrections

Here follows a brief discussion of applied corrections to the most important errors which could be corrected for. The actual corrections applied for each instrument type can be found in the Matlab code given in Appendix 2.

4.8.1 Linearity correction

The output of a radiometer measuring global irradiance should be direct proportional to the incoming solar radiation. This is seldom the case. But hopefully the deviation is negligible. For this study the non-linearity values of Kipp and Zonen CM5 and CM11 has been taken from IEA (1984). And the linearity of the Kipp and Zonen CM2 and CM3 are assumed to be similar to that of CM5.

The algorithms are normalized to 600 Wm^{-2}, which is an assumed average irradiance valid for a typical calibration. If this is not the case and a representative irradiance for the applied calibration is known the correction algorithm is adjusted.

4.8.2 Offset correction

The so called offset in the recording of irradiance was noted early but not much attention and quantification wasn't done until recent years. Therefore, this important effect cannot be corrected for the Ångström and Kimball pyranometers. Although, the magnitude is small it will sum up to considerable values; e.g. if monthly values are considered.

Based on data provided by Carlund (personal communication) a simple approach has been done to correct for this error for later instrument types. There is a clear difference between types of instruments studied and also between ventilated and un-ventilated units. As the actual instruments in use in Stockholm can't be studied one has to make a rough estimate. The conceptual model is as follows.

The instruments in the past have most probably been calibrated without any correction for the offset. Therefore, the calibration constant itself inherits a correction for the offset. It is plausible that irradiances recorded during conditions similar to the conditions for a typical calibration may not be severely affected by the offset. But, the offset exists in various degrees for all values and contributes in a systematic way to offset the daily, monthly and yearly values if not corrected for.

For unventilated CM5 and probably also for CM2 and 3 the offset is about -6 watts during clear skies (calibration conditions) as found by Carlund (personal com.). If the calibration is made without any correction for the offset the found calibration factor will be about 1% too large. Therefore, the calibration factor has been adjusted by a factor 0.99 for unventilated CM2, 3 and 5s.

The actual offset has been modelled as using the following algorithm for an unventilated Kipp and Zonen CM2, 3 or 5: Offset = $-6*S_{rel}$ Wm^{-2}, where S_{rel} (0-1) is the relative sunshine duration for the hour. The algorithm gives negative numbers (-6 to 0 Wm^{-2}) that should be subtracted from the global irradiation. The irradiance is reduced by 0.99, but increased by a few watts depending on the sunshine duration.

For a ventilated Kipp and Zonen CM5 the offset is very different. As before the assumption is that the effect of the offset is included in the calibration constant. But in this case it leads to an increase of the corrected calibration constant with about 1.005. According to the study of Carlund it can roughly described by Offset = 2.5+2*(1-Srel) Wm^{-2}, where Srel (0-1) is the relative sunshine duration for the hour. The algorithm gives positive numbers (≥2.5 Wm^{-2}) of the offset that has to be subtracted and thus the overall global irradiation will be smaller after correction although the factor 1.005 is applied. The ventilation of the pyranometer in Stockholm is assumed to be introduced starting in early 1973.

As the automatic station started at KTH-site offset-correction was introduced in 1983 using the night-time values as proxies. The study by Carlund (pers. Com.) showed that this correction for the ventilated Kipp and Zonen CM10 slightly underestimated the offset for low cloudy conditions. But, as the calibrations are made at these cloud-free conditions without offset corrections the remaining effect of the offset would probably be low (less than a watt). Also the ventilated Kipp and Zonen CM21, used after the upgrade in 2007, suffers from an offset. And also this seems to be slightly underestimated, if the night-time offset is used for correction. But the magnitude of this difference is small and probably negligible in this context.

4.8.3 Temperature dependence

The two testing institutes of NARC (US) and SP (Sweden) found in their laboratories that the temperature dependence of the K&Z CM 5 was about -0.11%/°C. Data were taken within the temperature interval -15° to +35°C, IEA (1984). The sensitivity of the instrument decrease with increasing temperature. For the K&Z CM5 instrument type five units were tested and interestingly the results differed only slightly, pointing at the fact that the characterization can be applied to any CM5-unit although there will remain some uncertainty. For the K&Z CM10/11 the temperature dependency was found to be small within the normal interval of ambient temperatures; probably within one percent, IEA (1984).

As the temperature of the instruments used in Stockholm was not recorded an eventual correction has to be based on e.g. temperature observations from a nearby meteorological station. For the older part of the series there might only be three temperature observations available per day and thus hourly temperature data has to be interpolated. These factors will certainly contribute to the uncertainty in the applied correction. However, it is assumed that applying a correction will reduce systematic differences between different times of the day and between different times of the year.

For data before 1945 only daily values of global radiation are available with few exceptions. This makes it necessary to make more assumptions and thus the temperature correction will be more uncertain.

The algorithms are normalized to 20˚C, which is an assumed temperature valid for a typical calibration. If this is not the case, and a representative temperature for the applied calibration is known, the correction algorithm is adjusted.

4.8.4 Directional responsivity

The sensitive part for radiation of the pyranometer, measuring global irradiance, should be a flat horizontal surface. For a perfect sensor the response to incoming radiation should be proportional to the cosine of the angle of incidence and the response should be independent of the azimuth angle. For most instruments this is not the case. In characterization the deviations from a perfect response is often referred to as the cosine and the azimuth error respectively.

5 Other types of errors

5.1 Rime and frost

There exist other types of errors in the chain of measurement. One example is shown in Figure 5.1, viz. rime on the dome. Before the introduction of ventilators in the 1970-ties this error occurred in Stockholm many days every year during the winter. In the example (31st of March 1957 a sunny day) one can see that in this case the measured radiation is increased dramatically after 7 (time increases from right to left) until the rime disappears just before 9. Notable is that the evaluator of the chart has not observed that something is wrong!

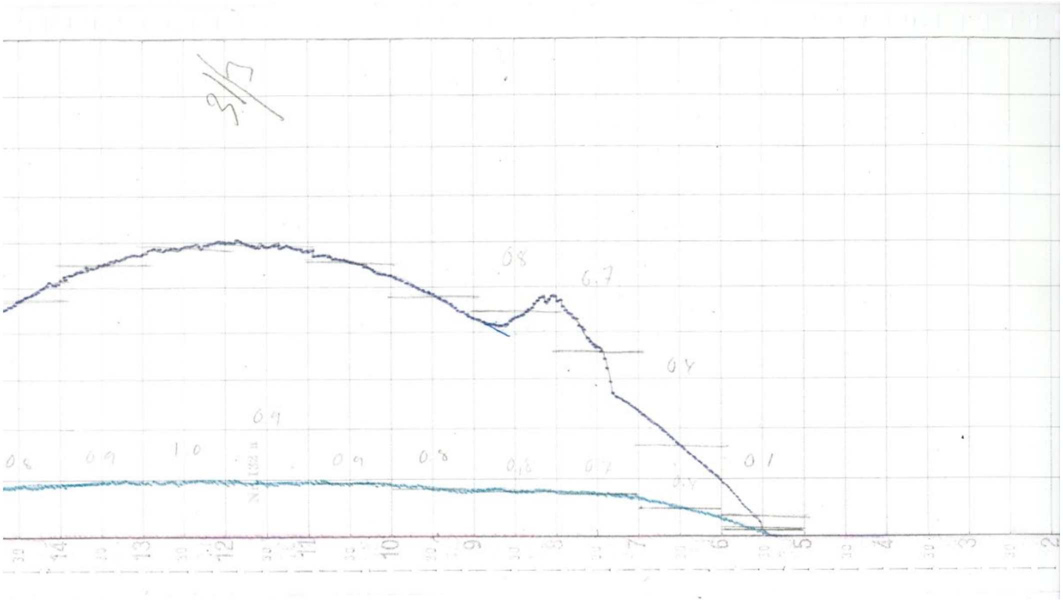

Figure 5.1 A paper roll registration from 31 March 1957. Note that time (true solar time) goes from right to left. There are three curves. The top one is the global radiation, the middle one is the diffuse solar radiation and at the bottom is a zero it's from this zero-line the readings should be related, as the paper may not always be perfectly adjusted.

According to personal communication the ventilator was introduced in Stockholm around the year 1973. When the institute was relocated to Norrköping the instrument at Bromma probably wasn't equipped with a ventilator until 18th of April 1979. During the winter 1978/79 all stations, in the Swedish solar radiation network, were equipped with ventilators. Therefore, there is probably a gap in ventilation in the Stockholm series for the period summer 1975 to April 1979.

Many times with rime conditions it will reform within ten minutes after it has been removed. If the rime is very thick, more like frost, there can be a decrease of radiation instead. Therefore, it's important that the evaluator of the chart strips has good knowledge of this phenomenon.

Many unphysically high values were recorded during the winter-half-year in the old part of the series. These values have, if detected, been reduced in the dataset. It is most likely that there still are a large number of slightly high values left in the dataset. Over longer periods of time they may partly be compensated by low values caused by snow and thick rime on the dome.

5.2 Obstacles

Another type of error is caused by obscuring obstacles in the surroundings. Solar radiation stations should be located with a relatively free horizon. But this cannot always be fulfilled. In high latitude stations the sun rise and set in a wide range of azimuths. Ideally in Stockholm the horizon has to be free from obstacles from north-east over to north-west (positions where the sun rise and set), which is more or less for all azimuths. This has not always been the case and at some hours in the morning during the Summer-half-year there has been a shadow on the instrument. It can be seen in e.g. Figure 3.3 between about 5.00 and 6.25 true solar time, where there is a dip in the record. Many of the evaluators have made a correction for this on sunny days, but not always. For other hours of the day or during cloudy days the reduction to the global radiation from this obscured part of the sky is minimal.

5.3 Unlikely high or low values

Using a data set with daily global radiation the values can easily be checked for physically possible high values. This is done by dividing daily values of global radiation, G, by the corresponding extraterrestrial values, G_{ex}. In Figure 5.2 below only values from the Summer-half-year are plotted.

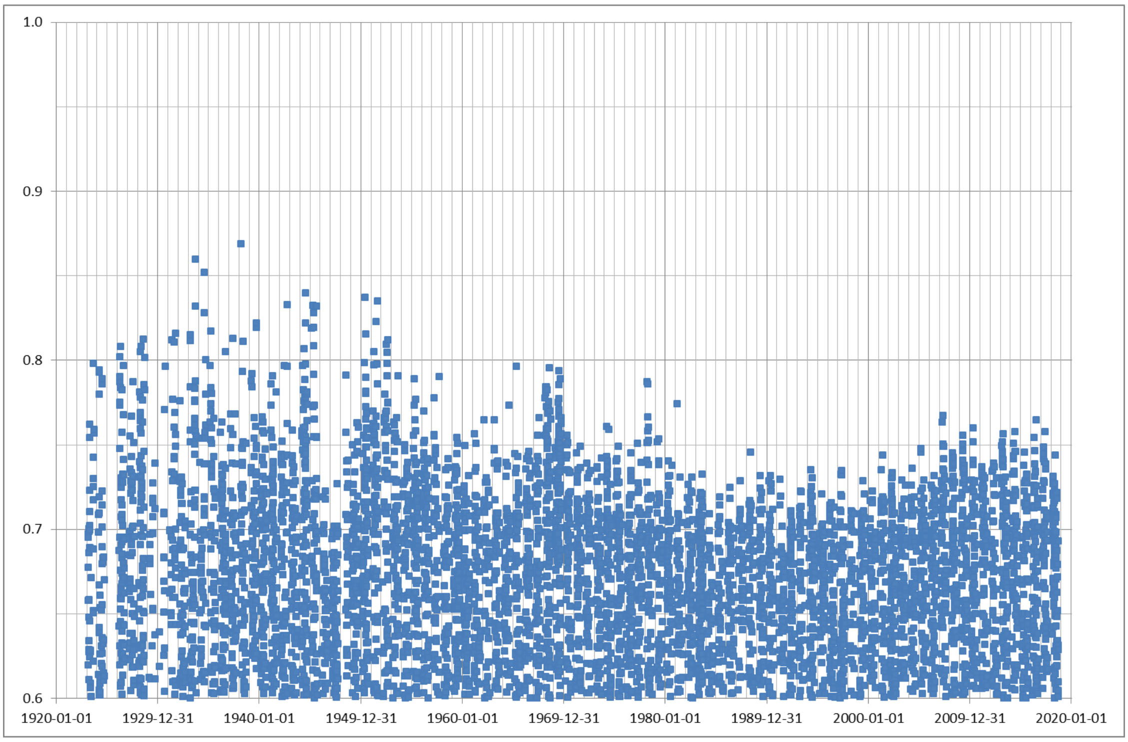

Figure 5.2 Daily G/G_{ex} for summer-half-year (15 Mar - 15 Oct) Stockholm 1923-2018.Used to find periods where "sunny" days deviates, see text. This graph presents the status during the process, not the final corrected data.

In the same way one should expect that sunny days in general during summer shouldn't give too low daily-ratios. Of course there might be individual sunny days where thin cloud or aerosol layers can attenuate the radiation.

The reason to exclude the winter-half-year is that those values often in the past were affected by rime, snow and frost on the dome. The winter values are also often small numbers and thus small errors in the evaluation might give high uncertainty in the calculated ratio.

A few comments to the use of daily extraterrestrial radiation as a norm for global radiation could be valuable to anyone who will or who have used this tool. To make a proper calculation is essential. Even small differences or simplifications in the applied algorithms may cause incorrect seasonal variations of the order 5% for some periods of the year if compared to a more accurate code. One cannot use one year of daily extraterrestrial radiation as a proxy. This is easily seen if you shift the data by one step as will more or less happen in the four-leap-year cycle. Such a shift will cause 2-3% error in the winter.

Using the fact that data collected from 1983 have a good quality one could easily see that the maximum ratios most probably should be less than 0.78 (*ad hoc value*) for Stockholm. The slightly lower ratios found in the 1980-ties and 1990-ties are probably caused by the two strong volcanic eruptions of El Chichon in spring of 1982 and of Pinatubo in June 1991. After the year 2000 the effect of the eruptions on the global radiation is probably small. Therefore, the clearest days at the end of the series can be used as a rough upper limit of the ratio G/G_{ex}.

Prior to 1983 there are a lot of daily ratios slightly larger than 0.78. The methods of evaluation and the characteristics of the used instruments can partly explain some of the scatter in these daily ratios. But this is not enough to explain ratios close to and above 0.8.

In the following sections there will be a discussion on some of these high and low ratios.

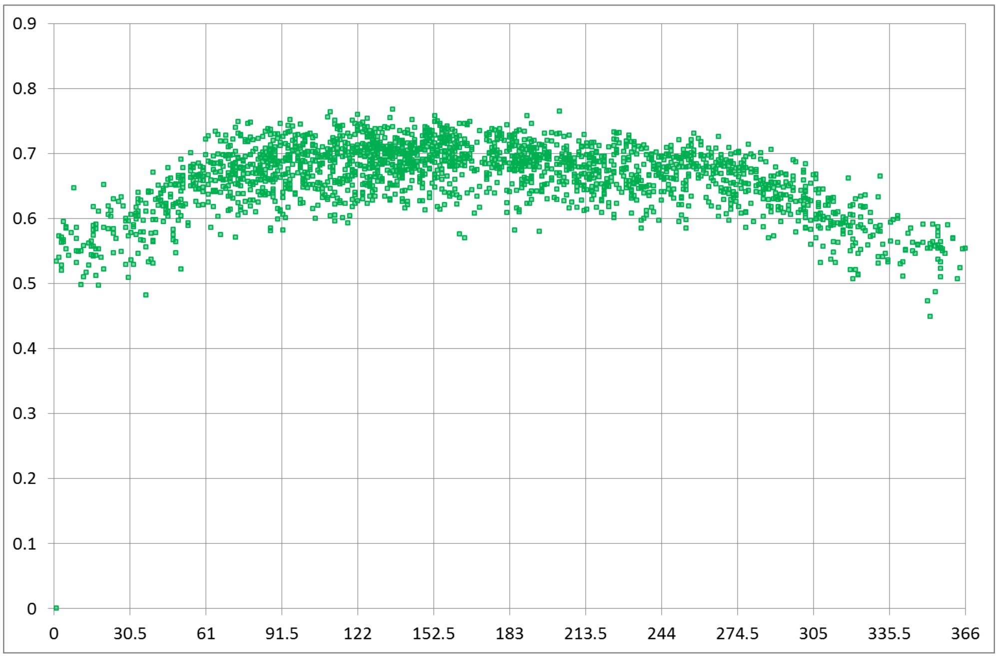

Figure 5.3 The daily relative global radiation, G/G_{ex}, for "sunny days" i.e. with relative sunshine duration ≥0.78 Stockholm-KTH 1983-2018 plotted versus day-number (1-366).

In Figure 5.3 above, one can see the ratio G/G_{ex} for the sunniest days for the period 1983-2018 when we have the highest quality of the measurements of both global irradiance and sunshine duration. Of course there is a scatter due to eventual cloudiness, variation in atmospheric absorption due to variable water vapor and ozone and scatter due to aerosols. The latter varied a lot for some years caused by the eruption of the volcanos El Chichon and Pinatubo.

The interesting climatological feature is the "upper limit" of the ratio and its variation over the year. A plausible assumption would be to expect a minimum close to the winter solstice and a maximum around the summer solstice. The minimum can be seen in December and into January. But, the maximum values are shifted towards spring. The highest values can be found over an extended period from mid-March to July.

The overall explanation is probably that the atmosphere contains less water vapor early in the year and more and more in the later parts of the summer. But, some of the high values in March and April are probably partly explained by multiple reflection effect (sky and ground) when snow cover was present.

5.3.1 Period 1922 to 1945

During this period it seems to be several factors that contribute to the uncertainty in the daily values and thus to the existence of high ratios G/G_{ex}. The evaluation of the daily value, the absolute calibration of the instrument and recording system and instrument characteristics seems to add up to relatively large uncertainties.

5.3.2 Period 1945 to 1952

Although a new instrument, the Eppley-Kimball pyranometer, was introduced similar drawbacks continued to hamper the overall uncertainty. This continued also in the beginning using the Kipp and Zonen CM3 in 1951.

During this period there is a dip in the highest ratios during 1946 and 1947. Possible explanations might be that there were not any sunny days during these years or that the atmosphere was extremely turbid e.g. due to volcanic eruptions. Both these hypothesis can be ruled out. Examining the data during the summer half year one can see that there are a number of hours during the day where it is registered 10.0 scale units. This means that the instrument output is out of scale of the recording unit. This effect of course affects the days with most irradiation.

From about 1953 calibration and data acquisition methods seems to have improved slightly. But, as will be seen in next section there were still problems.

5.3.3 Period 1966 to 1970

In Figure 5.2 the years 1968 and 1969 have some evident outliers i.e. high values that are off by some 5%. Therefore, these data were studied in detail. The original strip chart registrations can be found in the archive along with note books where the calibrations were calculated. Therefore, all original calibration-factors can be recalculated.

There were 7 calibrations of the instrument done in 1968 and 14 during 1969. The recalculations confirmed the used calibrations factors looks correct. But, they are usually randomly scattered within ±3%; caused by some minor miscalculations or disregarding of all decimals that easily can be kept using modern calculators. The observed calibrations are not always applied directly. Instead it seems that there has been a consideration where other calibrations and factors have been included to produce one calibration factor for each specific month.

Two pyranometers were calibrated at the same time using the shading disk method and an Ångström pyrheliometer. One was the pyranometer for global irradiance and the other one was a pyranometer used for monitoring diffuse irradiation. This opens the possibility to use another method for calibration namely the addition of components; i.e. global should be equal to diffuse plus the direct horizontal component.

Comparing the two methods for a number of calibrations in the years from 1966 to 1970 showed an average difference of about 3.6% (with a large scatter). This indicated that something was not correct.

In the note book[3] there was an interesting text added in September or October 1970. Translated from Swedish into English it says something like: “The instrument used for global radiation gives a too large reading when it is shaded … which cause a too large

[3] SMHI archive box D4:HDC

calibration factor". Unfortunately, there is no explanation to this discrepancy given in the note book. It's only laconically written "Orsak?" (Cause?).

To figure out how long period that was affected one cannot trust the note books either. According to the sparse notes found there the affected period was only June to September 1970. And the calibration constants for 1970 were adjusted accordingly. Older data were not.

There are no large changes in the data acquisition system noted for these years or the years just before 1968. One has to go back to the introduction of the instrument number 662560 on 29th of August 1966.

But, late 1966 and the whole of 1967 are not showing any clear outliers. This may be explained by remaining effects from the volcanic eruption of mount Agung. Therefore an assumption is that the period 29 August 1966 to 31 October 1969 should be corrected by reducing the values tentatively by 3.6%. It is unfortunate that one cannot be more precise regarding the size of the correction and more exact which period that should be adjusted. And naturally what was the cause of the discrepancy.

5.3.4 Period 1975 to 1983

This is the period at Bromma airport. The shift of place shouldn't be problematic, but for the available overlap in 1983 with the next site KTH one can clearly see a systematic change. A similar change was also observed for all other sites in the Swedish network. Typically, the old system gave roughly some 5% higher values in the summer time and the difference increased in the winter.

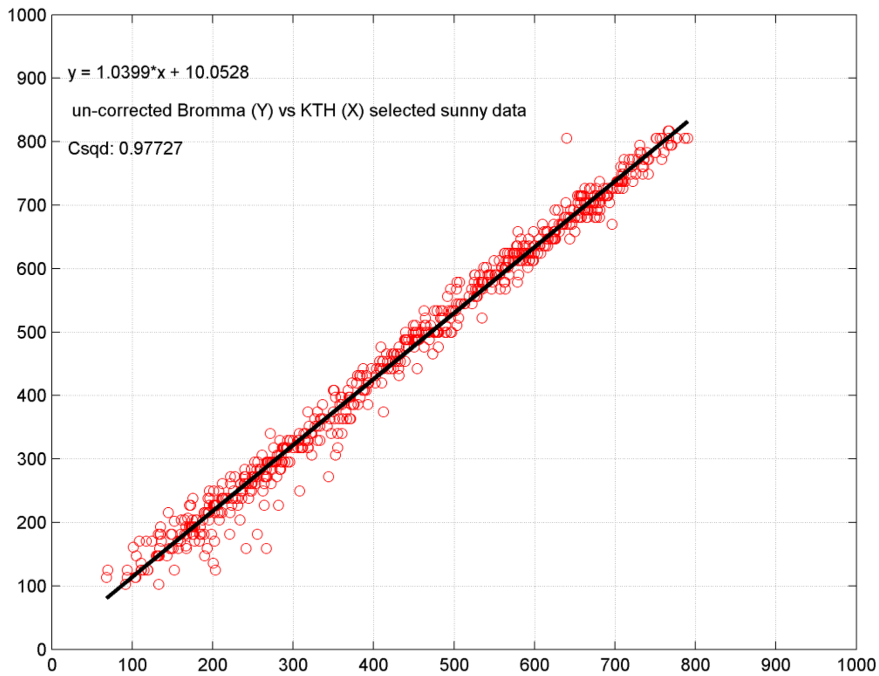

*Figure 5.4 Selected measured hourly data (sunshine duration> 59 min, global irradiation > 100 Whm^{-2}) **uncorrected** data from Bromma plotted versus KTH.*

Correcting the data for typical Kipp and Zonen CM5 instrument characteristics removed most of the seasonal behavior for Stockholm. The remaining seasonal variation is within the uncertainty of the corrections. Unfortunately, there was still a 5% higher global irradiation for the old system. This difference, not expected, was detected already in 1984 but an explanation couldn't be found at that time. In the following paragraphs a hypothesis is given along with a suggested correction.

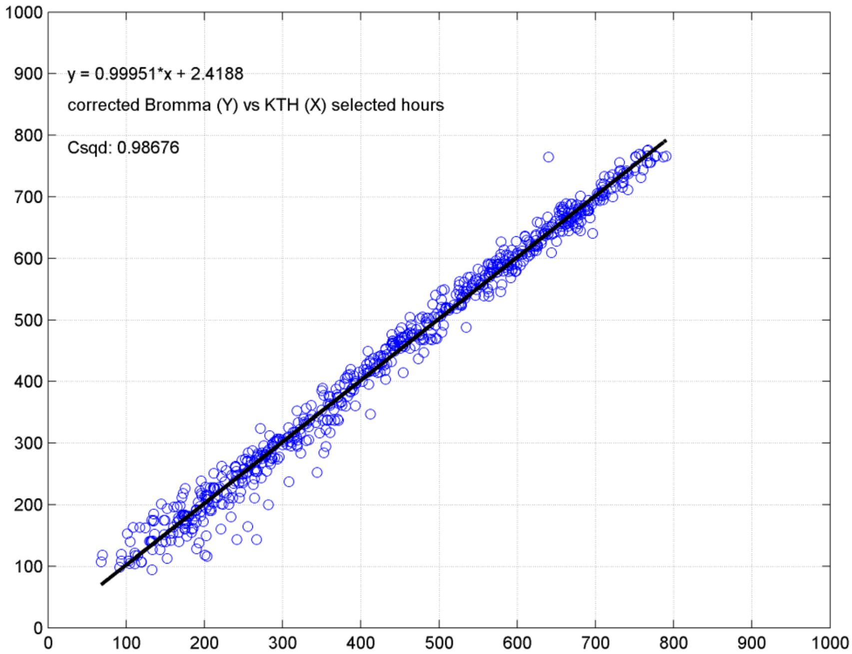

Figure 5.5 Selected measured hourly data (sunshine duration> 59 min, global irradiation > 100 Whm-2) ***corrected*** *data from Bromma plotted versus KTH. Some of the scatter remains and is due to the difference in time (true solar time was used for Bromma data and mean solar time at KTH) and to the fact that data are from two different sites. The difference in latitude is small.*

One change that occurred for this period was that instead of calibrating the pyranometers of the network using a pyrheliometer and the shading disk method a reference pyranometer was used. A hypothesis is that this may be the cause of the observed difference.

Looking in a binder with some remaining papers regarding old calibrations found in a shelf it seems that most stations in the Swedish network (including Stockholm) was calibrated using a pyranometer reference instrument starting in 1975 and 1976. It coincided with the relocation of SMHI from Stockholm to Norrköping. And this calibration method ended with the start of the automatic network in 1983. In Stockholm (Bromma) only a few data for the calibrations using a reference pyranometer is found in the archive. Therefore, one cannot be certain of the effect caused by this shift of calibration method.

So unfortunately, it has to be a rough guess. The few papers left indicate that it has been another Kipp and Zonen CM5 that has been used as reference calibrating the Stockholm-Bromma instrument. One thing that probably will simplify this is that "the same constant" has been in use at Bromma since September 1977. Nominally, it has changed but these changes are just recalculations due to a shift of strip chart recorder in 1979 and the shift to WRR in January 1981. There was a calibration and service visit in early September 1981 that seems to may have affected the sensitivity of the system. Comparing "clear days" with the extraterrestrial solar radiation indicates that there might be a small shift at this date.

Based on the factors mentioned in the previous paragraphs it is assumed that all values after 1 of September 1977 measured at Bromma have to be reduced by 2% until early September 1981 and then 4.7% for the rest of the Bromma-Stockholm series. The latter value is based on overlap data with KTH from 1983. For the other stations in the Swedish radiation network other percentages and break dates will apply.

These differences may occur in the following manner. A reference pyranometer e.g. the CM5 used in this case is probably calibrated using a pyrheliometer and the shading disk method a number of times during good conditions; i.e. the sun in southern sector of the sky (no azimuthal error), the sun high in the sky (low cosine), high irradiance and probably relatively high temperatures. When this reference instrument is used at the site of interest the azimuth may be slightly off south, the sun may not always be as high and thus the incoming radiation a little lower and on top of this the temperature might be slightly less than during the calibration of the reference. For a Kipp and Zonen CM5 all these factors work in the same direction i.e. the reference instrument will show a higher responsivity calibrating another pyranometer at less favorable conditions. The transfer of the calibration will thus give a slightly higher constant than it should.

How much larger or even smaller the transferred calibration can be, will depend on the actual conditions in relation to the conditions for which the calibration of the reference was deduced.

For Bromma only a few hours of parallel operation have been done. For other stations there exists cases where an integrator system has been used for the reference pyranometer and thus several days has been available for the transfer of the calibration. In those cases the used data definitely are not comparable to typical good calibration conditions and thus the possibility for a systematic difference will be even greater.

6 Handling of missing data

Measuring for many years will always have periods when the equipment fails and thus there will be gaps in the data set. One goal has been to fill these gaps with estimates of the global irradiance to retrieve complete daily and monthly data. The gaps should not be too long as this will increase the uncertainty for example studying the variation of the radiation climate.

Gaps during the night are of course no problem to fill in correctly. More severe are gaps in the middle of the day and during the summer as those periods normally have the highest radiation. As will be seen some gaps are easier to handle than others. Some major gaps will be commented more in detail in the following sections.

One method that will be used here for filling in the gaps is to apply the Ångström (1924) or more precisely the Ångström-Prescott-relation (1940). It is here defined as:

$$G/G_{ex} = A * S_{dur}/DayL + B;$$

where G is the observed daily global radiation, G_{ex} the extraterrestrial daily radiation, S_{dur} the observed sunshine duration and DayL is the astronomically calculated length of the day from sunrise to sunset. A and B are the coefficient found by linear fitting. In his original paper Ångström (1924) used an estimate of a clear sky value instead of the extraterrestrial radiation.

An important difference applied here is that all overcast values are treated separately. The linear relations are thus only based on days where the observed sunshine duration is larger than zero. The zero values are used to compute an average G/G_{ex}-value for overcast conditions. The motivation for this can easily be seen in the compiled regression data of Figures 6.1 and 6.2. There is a large difference between the average G/G_{ex}-value for overcast (OVC≈ 0.15) and the intercept value, B, for the linear relation (B ≈ 0.25).

Another relation (in this case non-linear) that will be used is the relation between total cloud cover and global radiation, similar to what Kasten and Czeplak (1980) found. Also here data for overcast is treated separately for the same reason.

6.1 Missing data 1922 to 1945 at Stocksund

There is some data missing in the early period. Unfortunately, there is few ancillary data available that can be used to fill the gaps. Sometimes the sunshine duration is observed at the nearby Vanadislunden. But as can be seen below, Figure 6.1, the correlation is not as good as it will be for later periods when both quantities are measured at the same site.

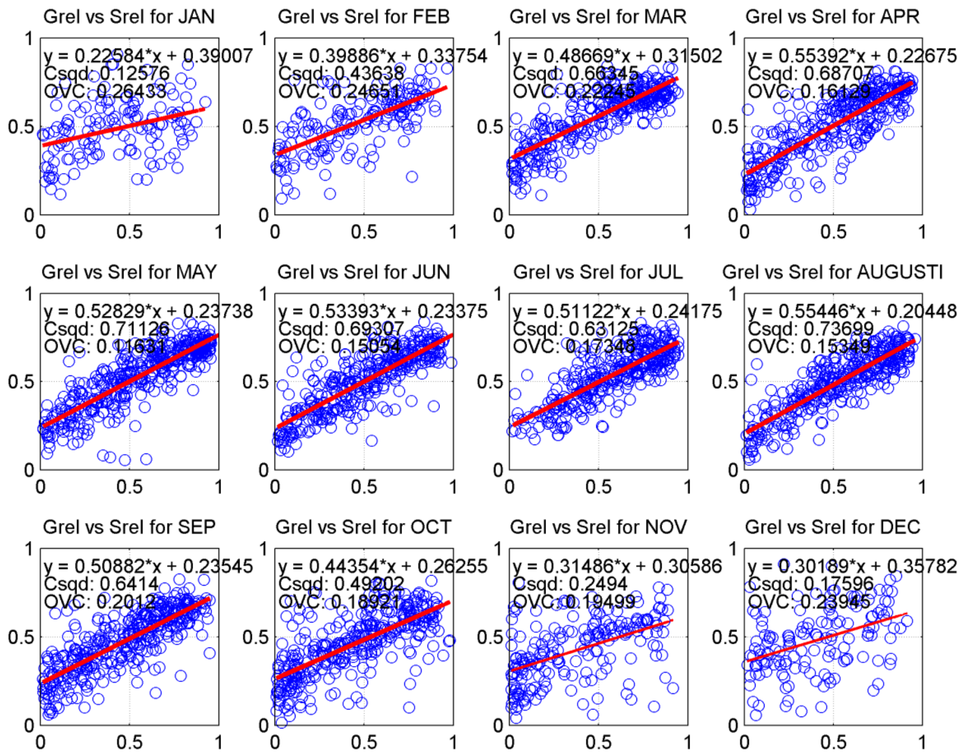

Figure 6.1 The Ångström-Prescott-relation plotted by month for daily global radiation divided by the extraterrestrial solar radiation versus the relative sunshine duration defined as measured hours of sunshine divided by the length of the day. In this graph all available daily data for the period 1922 to 1951 is plotted. Note: The measurements of the sunshine duration and the global radiation were not co-located during this period. The geographical distance was about 3 km.

The scatter in Figure 6.1 is relatively large especially in the winter, which in a large degree can be explained by the fact that the measurements weren't co-located. During days with variable cloudiness the measured quantities will be highly variable. Another contribution to the scatter during the winter half-year stems from days with rime and frost on the instruments.

The Ångström-Prescott relation in Figure 6.1 is deduced for daily relative sunshine larger than 0.1; i.e. the zero values for daily relative sunshine duration has not been included in establishing the linear fit. However, these values can be used to compute an average relative global radiation for days when the observed sunshine duration was zero. This value is given as OVC (overcast) for each month. It can easily be seen in the graphs that the intercept by the linear relation at zero sunshine always is larger than the OVC-value. This is also clear for later periods in the following Figures 6.2 and 6.4.

The used method to fill in missing daily values for the 1922-1945 period is described and discussed below.

6.2 Missing data 1946 to 1975 at Fridhemsplan

In the beginning of this period the measurements of sunshine duration and global irradiance were still not co-located, that started in late 1951. Another drawback in the beginning of this period was that the instruments were not heated and ventilated. But still, there is a clear reduction of the scatter just because of the co-location and this was further improved as the instruments became heated and ventilated.

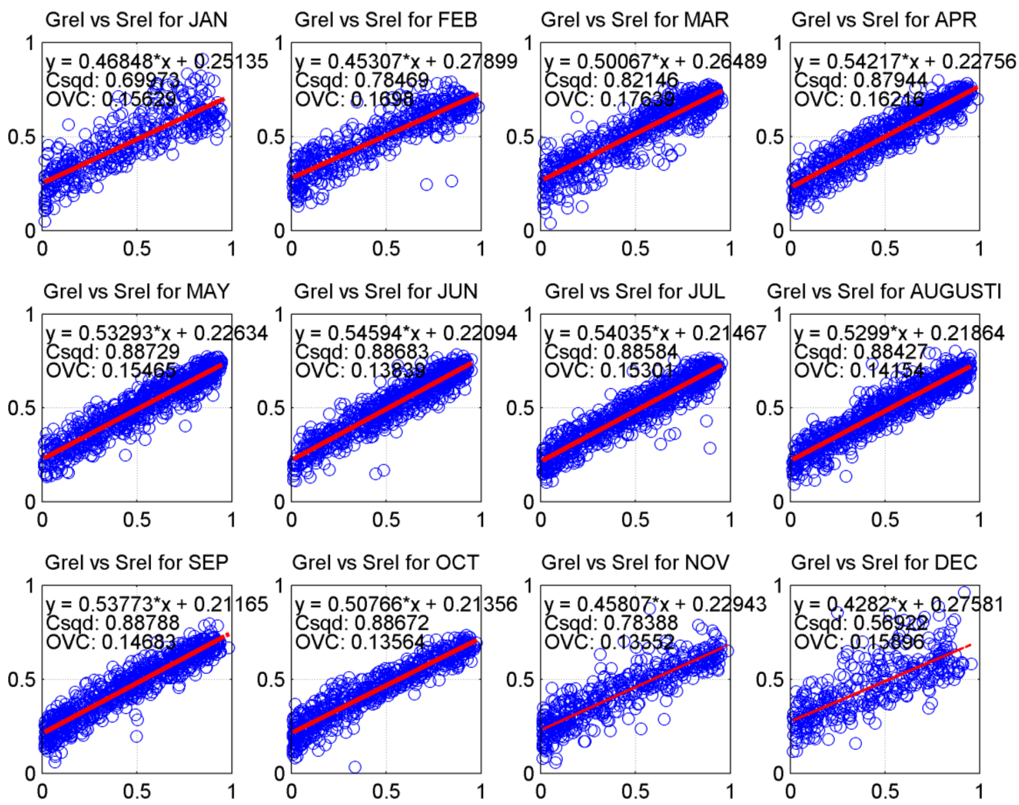

Figure 6.2 The Ångström-Prescott-relation plotted by month for daily global radiation divided by the extraterrestrial solar radiation versus the relative sunshine duration, defined as measured hours of sunshine divided by the length of the day. In this graph all available measured daily data for the period 1951 to 1982 is plotted. Note: The measurements of the sunshine duration and the global radiation were co-located during this period. But some of the data suffered from problems caused by frost in the winter time.

There is one long gap in the observations of the global radiation from January to July 1948 that has to be filled to have a complete data set. Fortunately, sunshine duration was measured at the nearby site Vanadislunden (about 3 km). As can be seen in Figure 6.1 there is a large scatter in the data plotting relative global radiation versus the relative sunshine duration when the measurements is not co-located. This scatter can easily be explained by local variation in cloudiness for each day.

Therefore, to minimize the uncertainty it is plausible that it is much better to use an Ångström-Prescott relation based on data where the instruments are co-located, for example as in Figure 6.2, than a relation when instruments were not co-located, as in Figure 6.1.

As for the previous figure the linear fit is also given in the graph for each month not using the zero-sunshine days. These are given as the average value OVC (overcast) along with the squared correlation coefficient (Csqd). To get an overview of the monthly Ångström-Prescott-relations the coefficients (A and B) used in the linear fittings are plotted.

In Figure 6.3 the yearly variation of the A and B coefficients can be seen for the two periods 1952-1982 and 1983-2018. The first period used heliographs for the sunshine duration and the later period used pyrheliometers (1983-2007) and Kipp and Zonen CSD (2008-2018). There is a clear systematic difference in A- and B-values between the two periods. Most of the difference is probably caused by the method of measuring the sunshine duration which causes small systematic differences. Therefore it is probably better to use the Ångström-Prescott-relation valid for the heliographs to fill in older missing periods; such as January-July 1948.

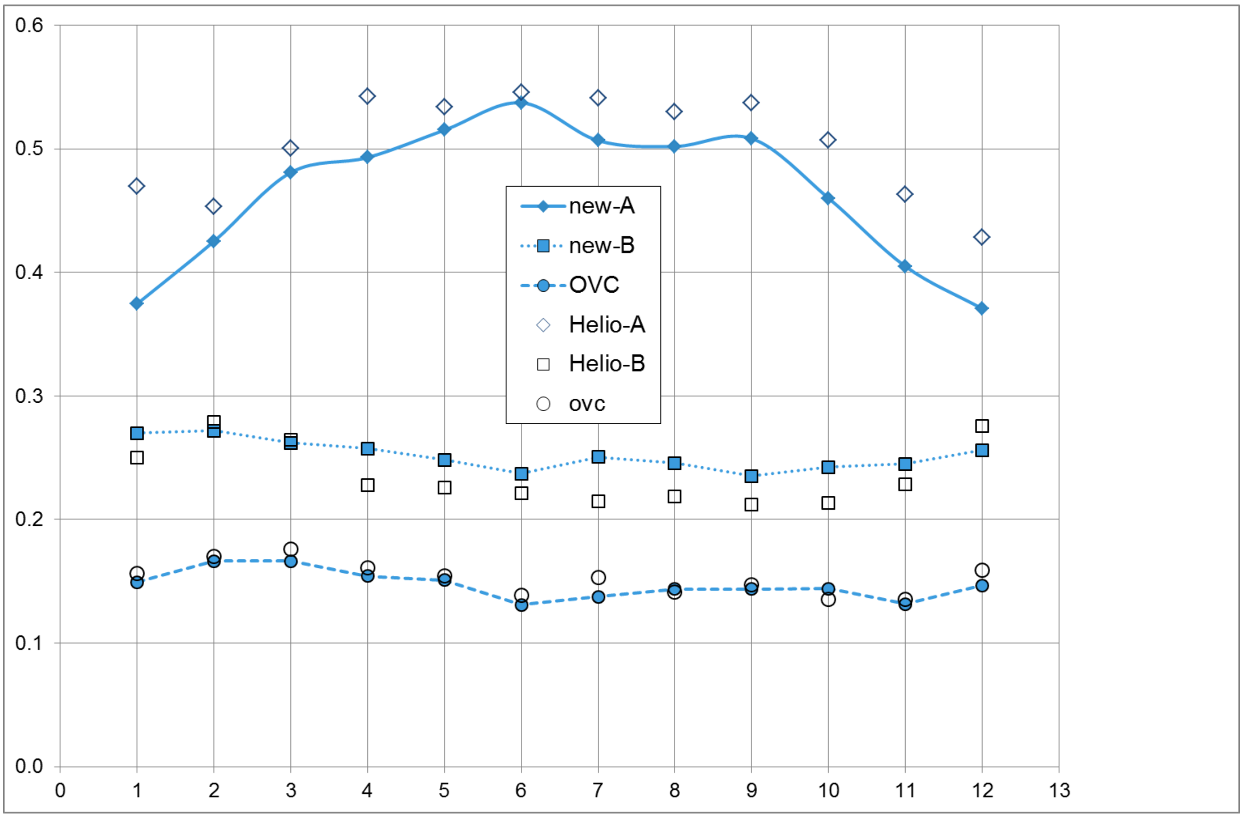

Figure 6.3 The coefficients (A and B) of the Ångström-Prescott- relation based on daily values plotted by month for two separate periods. The origin of the data can be seen in Figure 6.2 (Helio, 1952-1982) and Figure 6.4 (new, 1983-2018). The days with zero-sunshine duration are treated separately and presented as OVC which is the average of G/G_{ex} for each month (1-12).

An overall conclusion is that one should not mix Ångström-Prescott relations deduced from old heliograph data with data from modern instruments.

6.3 Missing data 1975 to 1983 at Bromma

As for earlier periods shorter gaps have been interpolated by the evaluators when the registration (paper rolls) were analyzed. For slightly longer periods single days or parts of days usually the records of sunshine duration were used to find nearby days with similar hourly values of sunshine duration. This manual interpolation was done hour by hour.

There is one long break in this period; namely April 1976. To replace this period the sunshine duration has been used to fill in the gap. The measurements are made at the same site. A relation between the relative global irradiance (measured divided by extraterrestrial) and of the relative sunshine duration (measured divided by day-length), S_{rel}, was established for the whole period using the days from 15 March to 15 of May, i.e. days centered on April.

The found relation is: $G/G_{ex} = 0.5502*S_{rel} + 0.2343$ for days when $S_{rel}>0$.

For more or less overcast days with $S_{rel}=0$ the average G/G_{ex} is 0.150. These computed values may vary slightly depending on the calculation of the extraterrestrial radiation and the length of the day.

To divide the data in two groups is motivated by the otherwise overestimation of the overcast days as was demonstrated in earlier sections. On average modelled values for days with no sunshine (overcast days) will be highly uncertain. The expected standard deviation from the applied average is roughly ±50% for overcast days. On the other hand these values of global radiation are much lower than the more sunny days. The non-overcast days can be computed with a standard deviation of about ±12%. The more sunny days will have an even lower standard deviation.

The uncertainty of the global irradiation of individual days is thus high, but for a longer period (e.g. a month) it will become lower. The more exact value will depend on the mixture between cloudy and sunny days.

6.4 Missing data 1983 to 2018 at KTH

In general hourly gaps have been filled in automatically by radiation modelling. In the early parts of this period a parameterized simple radiation model (JOS) using synoptic cloud observations was used; Davies et al. (1988). During the 1990-ties the input data from synoptic observations degraded and the modelling was replaced by the SMHI STRÅNG-model, Landelius et al. (2001). In some cases gaps has been filled by rough manual interpolation.

One major gap occurred in July 1998. At that time neither the JOS-model nor the STRÅNG-model was available and the sunshine duration observations also had a gap for the same period. How this gap was filled will be described below.

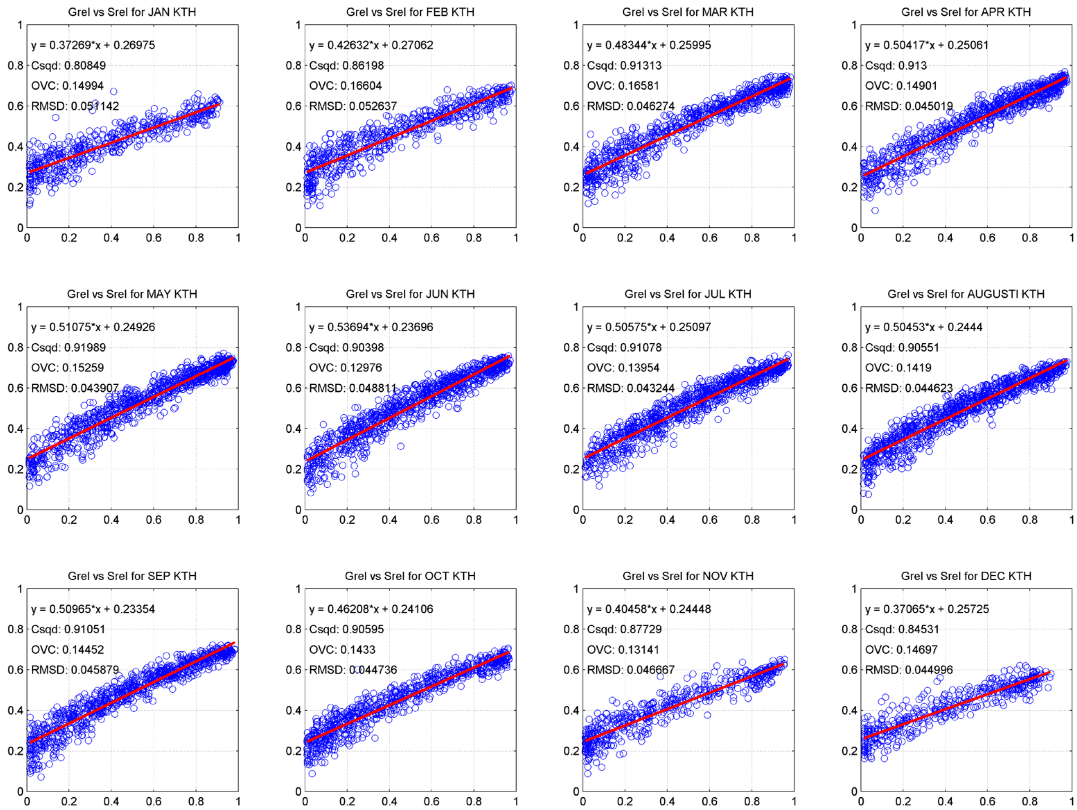

Figure 6.4 The Ångström-Prescott relation, plotted by month, for daily global radiation divided by the extraterrestrial solar radiation versus the relative sunshine duration, defined as measured hours of sunshine divided by the length of the day. In this graph all available measured daily data for the period 1983 to 2018 is plotted. Note: The measurements of the sunshine duration and the global radiation were co-located (KTH) and also co-sampled during this period.

An alternative is to use cloudiness as a proxy for the global radiation. Therefore, relation between the cloudiness and the global radiation were examined, Figure 6.5.

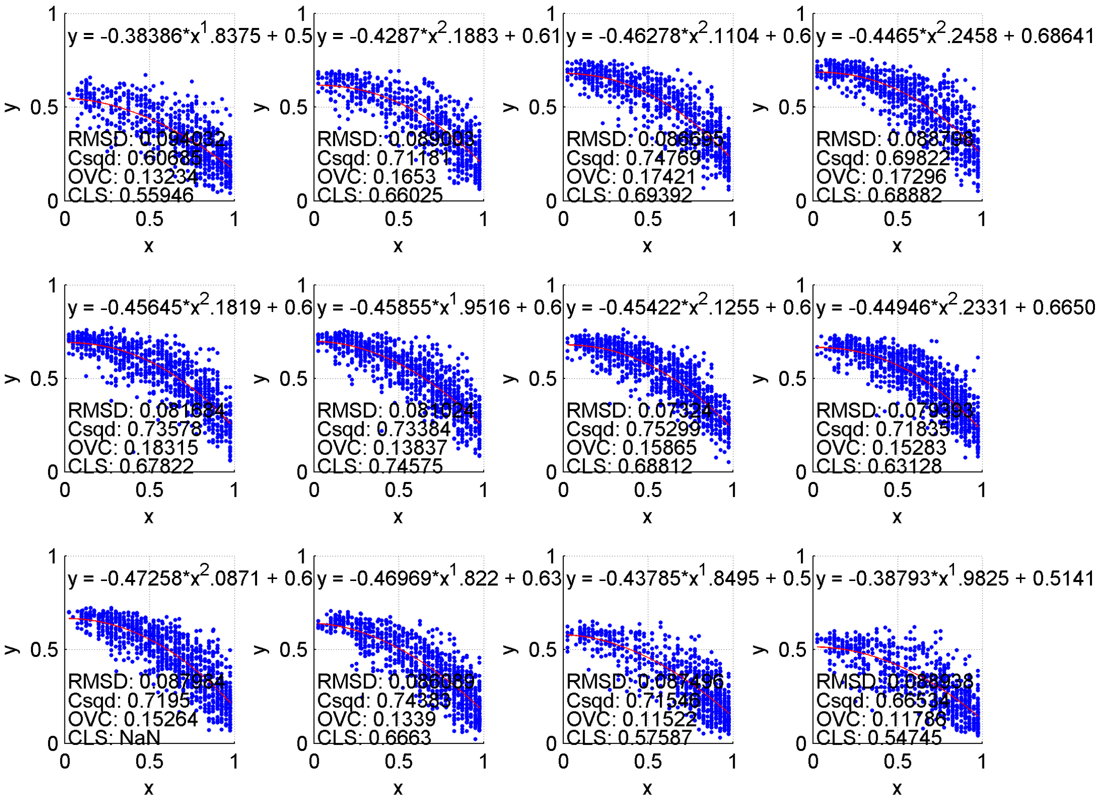

Figure 6.5 A non-linear fit (red line) of daily global radiation divided by the extraterrestrial solar radiation versus a weighted value of the cloudiness of the day for each month of the year. First row Jan, Feb, Mar and Apr etc. In this graph all available measured daily data for the period 1983 to 2018 is plotted. Note: The measurements of the global radiation and the cloud observations were not co-located; the distance is about 3 km.

The cloudiness, observed three times a day at Observatoriekullen in Stockholm (1983-2018), was weighted such as the morning and evening observations have the weight of one and the close to noon observation has the weight of three. The number is then normalized to a scale from 0 to 1, where 0 corresponds to a cloud-free day and 1 to an overcast day.

In Figure 6.5 the days where the observed weighted and normalized cloudiness is 0 or 1 are omitted from the non-linear fitting. However, the observed average values of the G/Gex-ratio for those days are given in each sub-plot as OVC (overcast) and CLS (clear sky). The omission of the clear sky values was because the linear fitting program didn't like zero-values and the omission of the overcast values was because they deviate systematically and thus have a quality reducing influence on the relations. As for the Ångström-relations using sunshine duration it is better to treat these values separately.

The found non-linear fit should be interpreted as $G/G_{ex}= a*(C_{rel})^{b} + c$; where a, b and c are coefficients, C_{rel} is the normalized relative cloudiness of the day. The squared correlation coefficient is also given and it has values roughly in the range 0.60 to 0.75. For July the relation is $G/G_{ex}= -0.45422*(C_{rel})^{2.1255} + 0.67914$ with a squared correlation coefficient of 0.75299. The average G/G_{ex}-ratios for overcast and clear sky were 0.15865 and 0.68812 respectively.

7 Uncertainty estimates

In general regarding the uncertainty of the data one can distinguish three periods. The first 30 years with old types of instruments and data acquisition systems often shows a large scatter around plausible model calculated values. The documentation found in archives is sparse or non-existent making eventual corrections guesswork.

In the early 1950-ties newer instruments and data acquisition systems were introduced. The data were evaluated on an hourly basis making it possible to apply more precise corrections for various instrument errors. But still severe errors in data are sometimes evident.

The automation and introduction of new instrumentation starting 1st January1983 proved to produce data of much higher quality than before. And at the upgrade in 2007 a slight improvement was done that reduced the uncertainty further.

The uncertainty analysis presented in this section is based on information and methodology described in Cook (2002) and JCGM 100 (2008) and they are made for daily values. The calculations are made using an Excel-spreadsheet as in Figure 7.1 following the worked example of Cook (2002). Many details are open for discussion as they are estimates and sometimes even rough guesses. However, from the spreadsheet one can easily see which uncertainty components that dominates and that others are of minor importance for the overall result.

Uncertainty analysis for daily values of global radiation measured at Stockholm

Instrument Kipp and Zonen CM-21 pyranometer
Period 2007-2018

Uncertainty Component	needs corr for systematic component	Magnitude of syst.comp	Unit	for daily value A or B	Distribution	rough estimates relative u or a	Divisor	degrees of freedom vi	u(x)	sensitivity coeff c	standard unc. u(y)=c*u(x)	squared st unc u(y)^2	standard uncertainties to the fourth power divided by their degrees of freedom u(y)^4 / vi
Abs calibration	No			B	rectangular	0.01	1	5000	0.01	1	0.01	0.0001	2E-12
spectral resp	No			B	normal	0.01	1	5000	0.01	1	0.01	0.0001	2E-12
non-linearity	Yes			B	normal	0.002	1	125000	0.002	1	0.002	0.000004	1.28E-16
temperature resp	Yes			B	normal	0.005	1	20000	0.005	1	0.005	0.000025	3.13E-14
cosine	Yes			B	normal	0.01	1	5000	0.01	1	0.01	0.0001	2E-12
azimuth	No			B	normal	0.0025	1	80000	0.0025	1	0.0025	6.25E-06	4.88E-16
time-const	No			B	normal	0.001	1	500000	0.001	1	0.001	0.000001	2E-18
non-stability between calibr	No			B	normal	0.005	1	20000	0.005	1	0.005	0.000025	3.13E-14
offset	Yes			B	normal	0.005	1	20000	0.005	1	0.005	0.000025	3.13E-14
error in time	No			A	normal	n/a				1			
unc in registration	No			B	rectangular	0.001	1	500000	0.001	1	0.001	0.000001	2E-18
evaluation of registration													
method of evaluation	no			A	normal	n/a	2			1			
significant digits	no			B	rectangular	0.002	1	125000	0.002	1	0.002	0.000004	1.28E-16
rounding in integrated values	no			B	rectangular	0.002	1	125000	0.002	1	0.002	0.000004	1.28E-16
other suorces of uncertainty													
rime, frost, dew, rain, dirt				B	rectangular	n/a							
humidity inside				B	rectangular	n/a							
tilt of instr				B	rectangular	n/a							
missing value /interpolation				A	normal	n/a							

CONCLUSION
Daily values measured by the Kipp and Zonen CM21 pyranometer have an uncertainty (95%) of about **±4 %**
Note that the precision may be about 2%

Sums	**0.000395**	**6.09E-12**	
Combined standard uncertair	**0.019881**		sqrt of sum
Effective degrees of freedom	**25633**		From Welch-Sattertwaite equation
Coverage factor (95%) k=	**1.96**		Student's t-table gives this from nbr of freedom minus one
Expanded uncertainty	**0.03897**		

Figure 7.1 Example of analysis of the uncertainty for daily values of global radiation recorded at Stockholm 2007-2018 with the CM21 pyranometer.

The same procedure has been applied to the period when the Ångström, the Kipp and Zonen CM5 and CM11 pyranometers were used. For the other instruments; Aurén, Kimball-Eppley and Kipp and Zonen CM2/3 the uncertainties are assumed to similar as for the investigated instruments. The results are summarized in Table 7.1.

These uncertainty estimates are supposed to be valid in general when the monitoring has worked properly. There are most likely global radiation values that are severely erroneous due to e.g. rime or fatal errors by the operator which has not been detected in the reprocessing. Interpolated daily values in general can mostly to be regarded having a similar but slightly higher uncertainty.

One can get an idea of the daily/monthly uncertainty from available calibration campaigns e.g. during the Baltic region pyrheliometer intercomparison in 2012, when also a calibration of pyranometers took place, Carlund (2013). Data accumulated over six days were mostly within ±1% of the reference. Here we can assume that the participating instruments were well kept pyranometers and the radiation represented sunny conditions.

Therefore, in general the *ad hoc* estimates used here are relatively pessimistic so for modern measurements the absolute uncertainty may be a little lower. And one should also keep in mind that an estimate of the precision would give much lower values.

Table 7.1 Expanded absolute uncertainty (2σ) *estimates for daily values measured at Stockholm 1922-2018 for days when everything operates as it should.*

Instrument	**Approx. period**	**Uncertainty (%)**
Ångström #2	1922-1930	15
Ångström #40	1931-1945	15
Aurén solarimeter	(1938-1942)	15
Kimball-Eppley	1945-1951	13
CM2/3	1951-1975	11
CM5	1975-1983	10
CM11	1983-2006	5
CM21	2007 -	4

One could expect monthly and yearly values to have a much lower uncertainty but that is not the case as a large part of the uncertainty is from systematic errors. Therefore, the reduction in the uncertainty going from daily to monthly values is small, with the exception for data after 1983.

A very *ad hoc* estimate of the monthly uncertainty has been done and is presented in Table 7.2. It is based on the daily estimates in Table 7.1 and on a rough guess of the random component of the daily uncertainty. On top of that a rough seasonal variation has been introduced. In principle the measurements are more accurate during the summer than during the winter.

Table 7.2 Expanded absolute uncertainty (2σ) *estimates for monthly values measured at Stockholm 1922-2018.*

Pyranom.	unc (%)	random comp	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Å-pyr #2	15	6	19.1	17.3	14.6	10.1	7.8	7.8	7.8	8.3	12.8	15.5	18.2	20.9
Å-pyr #40	15	6	19.1	17.3	14.6	10.1	7.8	7.8	7.8	8.3	12.8	15.5	18.2	20.9
Aurén	15	6	19.1	17.3	14.6	10.1	7.8	7.8	7.8	8.3	12.8	15.5	18.2	20.9
Eppley- K.	13	6	15.1	13.7	11.6	8.1	6.3	6.3	6.3	6.7	10.2	12.3	14.4	16.5
CM2/3	11	6	11.1	10.1	8.6	6.1	4.8	4.8	4.8	5.1	7.6	9.1	10.6	12.1
CM-5	10	6	9.1	8.3	7.1	5.1	4.1	4.1	4.1	4.3	6.3	7.5	8.7	9.9
CM-11	5	3	4.5	4.2	3.5	2.5	2.0	2.0	2.0	2.1	3.1	3.7	4.3	4.9
CM-21	4	3	2.5	2.4	2.0	1.5	1.3	1.3	1.3	1.3	1.8	2.1	2.4	2.7

Another thing one should have in mind is that the precision often is better than the absolute uncertainty. This could probably also be valid for the pyranometer measurements from Stockholm. The systematic errors are often of the same sign and type for the old instruments.

Many values in the long-term record have been modelled as described in the previous section. The uncertainty of these modelled values can be roughly estimated using the

RMSD for daily values as presented in Figures 6.2 and 6.4. For an individual modelled daily value a doubling of the RMSD would be a good estimate. If several daily values have been used to estimate a monthly value it is plausible that some may be too high and others can be too low. Thus uncertainty will be reduced.

It can also be seen from the figures that the sunny days have a smaller relative scatter than the more cloudy days. And that summer values in general have a lower RMSD than winter values; in particular for the cloud based model and less evident for the sunshine duration based model.

8 Final data and discussion

One aim of the project is to make all data available for further studies of the climate and specifically the radiation climate of Stockholm (Sweden). What type of long-term variations could we expect? Monthly and daily extreme values are also interesting to monitor and of course the typical yearly variation. To make this possible the following data set have been complied and some of them can be downloaded from the web sites below.

8.1 Final data sets

The final datasets are put in folders on the SMHI data servers, specified below. For those interested they can be retrieved from SMHI. But, daily and monthly data are also available for download from www.smhi.se

Recent hourly data can also be down loaded from "Öppna data" at www.smhi.se

8.1.1 Raw data files

The first part of the work was to digitize all old data in yearly Excel-files from publications. For later years hourly values exist, but before late 1945 most data are daily values and unfortunately for some periods only monthly values can be found. These values were scrutinized and eventually corrected using information found in the archive of SMHI. These data can be found in:

\\winfs\prod\UVOzon\G-Stockholm\FINALdata\BestRAW

8.1.2 Hourly data files

Based on the raw-data files for the years before 1983 and on available data sets for later years these data sets have been processed using available ancillary data and instrument characteristics to produce yearly corrected data. These files can be found here: \\winfs\prod\UVOzon\G-Stockholm\FINALdata\hourly also here is a READ_ME-file to explain the format.

8.1.3 Daily data files

Using the high quality data from later years two simple models using cloud or sunshine duration observations could be used to construct simple models. These models have then been applied to fill in missing days and months to get a final data set of daily values, which was compiled into one Excel file with daily values 1923- 2018. \\winfs\prod\UVOzon\G-Stockholm\data-mm\digitaliseradeDATA\BEST-data\dygnsdata\Day_1923_2018.xlsx

Also as a plain text file in the same place named: Day1923-1945.txt can be found in \\winfs\prod\UVOzon\G-Stockholm\FINALdata\daily . The data format is given in a READ_ME-file in the same folder but is presented here as well to give a hint of what can be expected:

Format:

Date	yyyy-mm-dd
Year	yyyy
Month	mm
Day	dd
day number	1-366
instr	xx.xx (see list of instruments)
eta	original raw data for the oldest series (most of 1927 Sep-1945 Sep)
CF	Original calibration factor applied
Q	Original global radiation published

best/corr Q	Original global radiation after control and correction of errors. Interp. replaced by model value
toWRR	conversion factor to get WRR
toWhm-2	conversion factor to get Whm-2.
Coscorr	for period when only daily values available a rough correctionfactor for the cosine-err is app
CF-corr	for some periods the used CF calibration factor has been corrected
Gcorr	The final corrected daily global radiation (Whm-2)
status	Indication of the status of the global rad value
Srel	Relative sunshine duration (0-1), mostly missing -999
Sdur	Sunshine duration (hours), missing periods -999
DayLength	Length of day (hours)
Ncloud	Total cloud cover as fraction (0-1) three observations are weighted, where 1 is overcast.
TempDay	Mean day temperature (˚C)
Gex	Extraterrestrial global radiation (Whm-2)
G-cloudModel	Modelled global radiation from cloud cover (Whm-2)
G-sdurModel	Modelled global radiation from sunshine duration (Whm-2)

Comments

Missing values -9 or -999.

In column "best/corr Q" interpolation priority is sunshine duration based model, cloud based model and in some cases where probably sunshine duration is affected by rime manual subjective values are given.

The quality flag for the period 1922-1982 is 1 or 2 for observed data, 3 for manually interpolated, 4 for modelled. If there are variations of the quality flag for the hours constituting the daily value the average is computed. That's why can find decimal values such as 1.23. The quality flag for the period 1983-2018 is given as percent observed and accepted data during a day; i.e. a value of 100 denotes only measured data in the daily value. A lower value therefore indicates a higher degree of non-measured values. An exception for this is July 1998 where all data are quality flagged 4. During this month all values were missing and thus all global radiation values are modelled.

The raw-data (eta and Q) is mainly of interest for checking the history of the data and the applied corrections.

For 1983 the final data Gcorr is from KTH, but in column Q the overlapping data from Bromma can be found. But, if the reader wants to make a new study of the overlap it is recommended to use the hourly data from Bromma found in the G1983.xlsx file see section 8.1.1.

8.1.4 Monthly data files

In the early period (1922 - 1931) there are monthly gaps in the **daily** file. About one third of the months in this period exist only as monthly values. The original daily values are lost. These monthly values have been roughly corrected in the following manner.

Luckily, there is a period with hourly values available published in Ångström (1928). These values can be corrected for the assumed cosine error of the old Ångström pyranometer. The effect on the daily and monthly values from this correction can thus be estimated and these correction values can then be applied on the period where only daily and monthly data are available. It is assumed that this correction makes data more consistent with later periods. But the uncertainty is large and one cannot be sure that this is the case as there are no raw data or daily data to scrutinize.

A final monthly data set is compiled from the hourly and daily values and the monthly values mentioned. Modelled values are inserted to have complete data for the 1922-2018-period. The data can be found in:

\\winfs\prod\UVOzon\G-Stockholm\FINALdata\monthly

together with a READ_ME-file to explain the format.

In the same folder there are also a set of other files containing sunshine duration, length of the day, extraterrestrial radiation and modelled global radiation (from clouds and sunshine respectively).

8.2 Discussion

8.2.1 Comparison versus earlier data

Using the data from previous section various plots can be produced. Here a few will be used as examples.

The first Figure 8.1 shows the effect of the data revision. Here the blue line is based on the original published data and the black line on the revised data set. The big dips of the blue line correspond to the incomplete years 1922 and 1948.

For some years there are relatively large changes and for the years after 1982 the changes are minor. There is a change in the interpolation of July 1998 but the effect is so small that it cannot be seen in this graph.

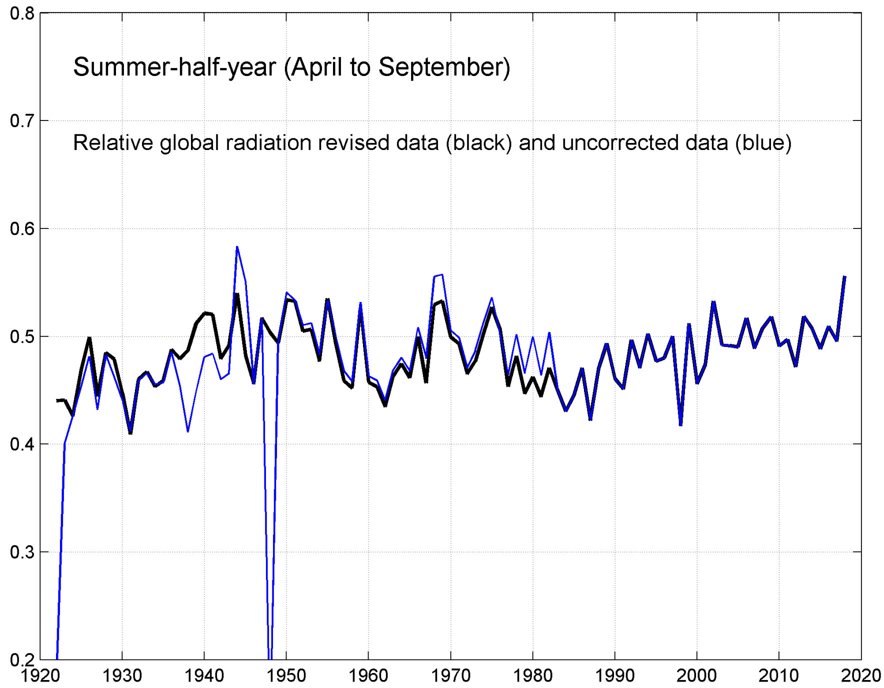

Figure 8.1 The uncorrected (blue) and the revised (black) relative global radiation for the summer-half-year, Stockholm 1922-2018.The years 1922 and 1948 are missing in the old data set but computed from sunshine duration in the revised data set.

The seemingly large changes that can be seen in Figure 8.1 from late 1930- into the 1940-ties were due to error in the absolute calibration. Another relatively large discrepancy is the one around 1980. That one is assumed to be caused by the use of a reference pyranometer instead of the more traditional shading disk method using a pyrheliometer.

And for all years small corrections are done for typical instrument characteristics; such as non-linearity, temperature dependency and directional responsivity (cosine, azimuth).

8.2.2 Comparison versus sunshine duration

Figure 8.2, shows the relative sunshine duration (red) and the relative global radiation for the summer-half-year (April to September) and their co-variation over the full period. The summer-half-year has been selected because it is the time of the year with the best quality data and it is also the time of the year with most radiation.

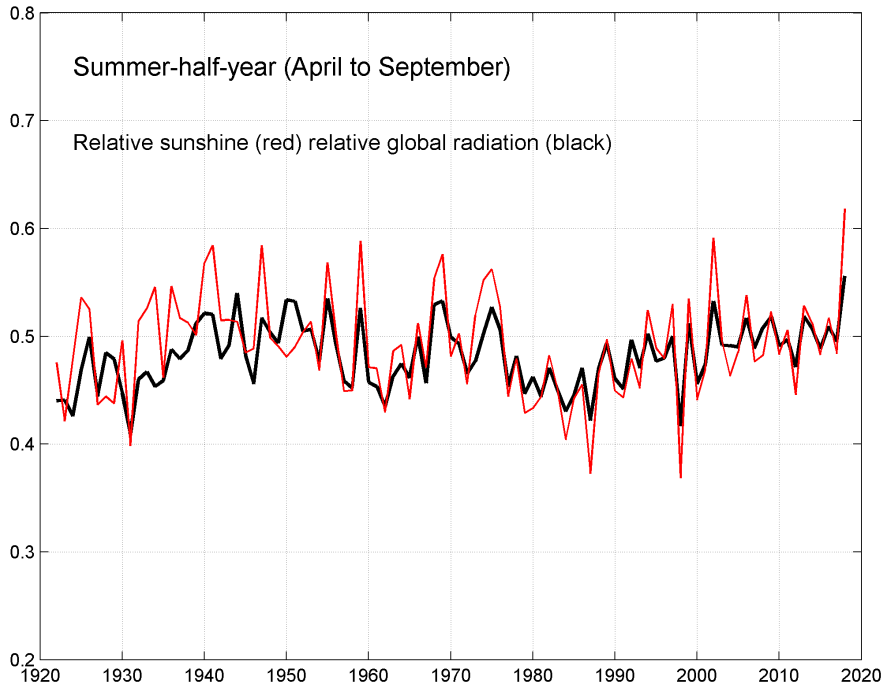

Figure 8.2 The relative sunshine duration and the relative global radiation for the summer-half-year (April to September) 1922-2018 in Stockholm.

The correlation between the relative sunshine duration and the relative global radiation is high, especially for the years after 1951. Late in this year the measurements of the two quantities were co-located. Before that the measurements were made at two sites. But, this may not be the only explanation to the lower correlation in those years. It is most probable that the quality of both sunshine and global radiation measurements were considerably lower.

Another feature worth noting is that the relative sunshine duration has a larger variation than the relative global radiation. This is of course due to the fact that sunshine duration is closely connected to the direct radiation, which has a character of on and off due to variation in cloud cover. The global radiation has a much smoother variation as there always is a diffuse radiation component.

8.2.3 Long-term variation

Looking at the long-term variation both quantities show a similar pattern, and the most extreme values (maximum and minimum) for the sunshine is confined within the period of the best quality measurements; i.e. 1983-2018.

As already stated the best data for the whole period are those from the summer half year. The winter half year (before 1983) is more affected by rime, snow, rain and less accurate instrument and recording system.

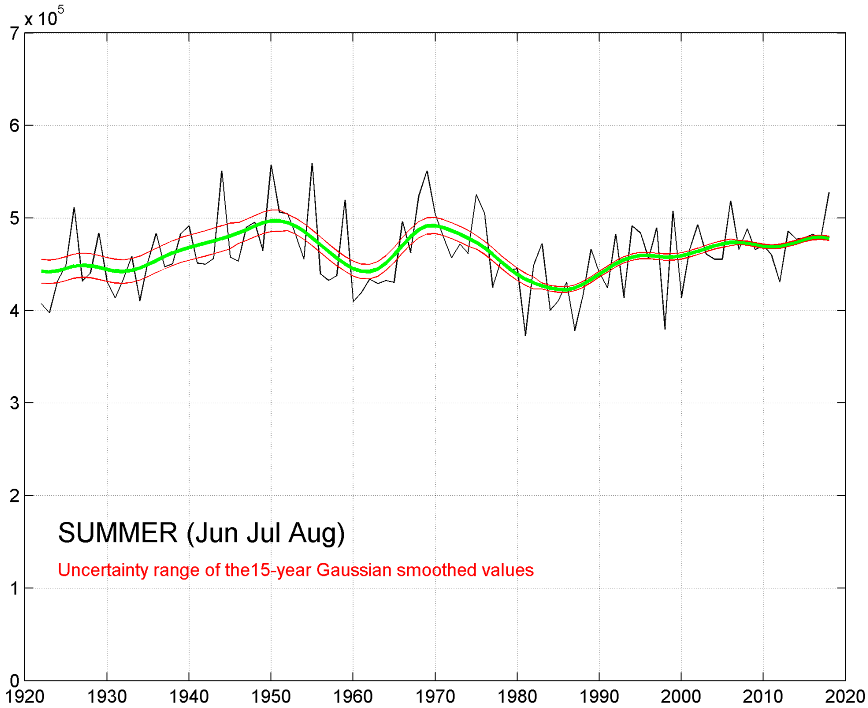

Figure 8.3 Global radiation (black) for the summer months (Jun, Jul, Aug) Whm^{-2} for Stockholm, 1922-2018. Also plotted are the Gaussian smoothed values (green) with an uncertainty estimate (red).

Therefore, the summer months are interesting for eventual trend studiers. The long-term variation is as follows. In the earliest part of the series there's a rise in the radiation up to around 1950. The maximum is followed by a decrease in the early 1960-ties and an upward trend to the early 1970-ties. The downward period after this is known as the global dimming which lasted to the late 1980-ties. After that we have had what is called a global brightening.

8.2.4 Comparison with other long-term series

In section 2.10 the Stockholm data is briefly compared versus modelled global radiation from CERA. In this section a few comments on comparison versus other long-term series of global radiation from nearby stations.

At Ås in Norway, close to Oslo, measurements for the period 1950 to 2003 Grimenes and Thue-Hansen (2006) show a similar variation as do the Stockholm data.

Another old and long series of global radiation is monitored at Wageningen in The Netherlands, Bruin et al. (1995). The relative global radiation from 1928 to 1992 for the Summer-half-year is plotted in Figure 8.4. Some of the systematic difference could probably be explained in a difference of the calculation of the extraterrestrial radiation.

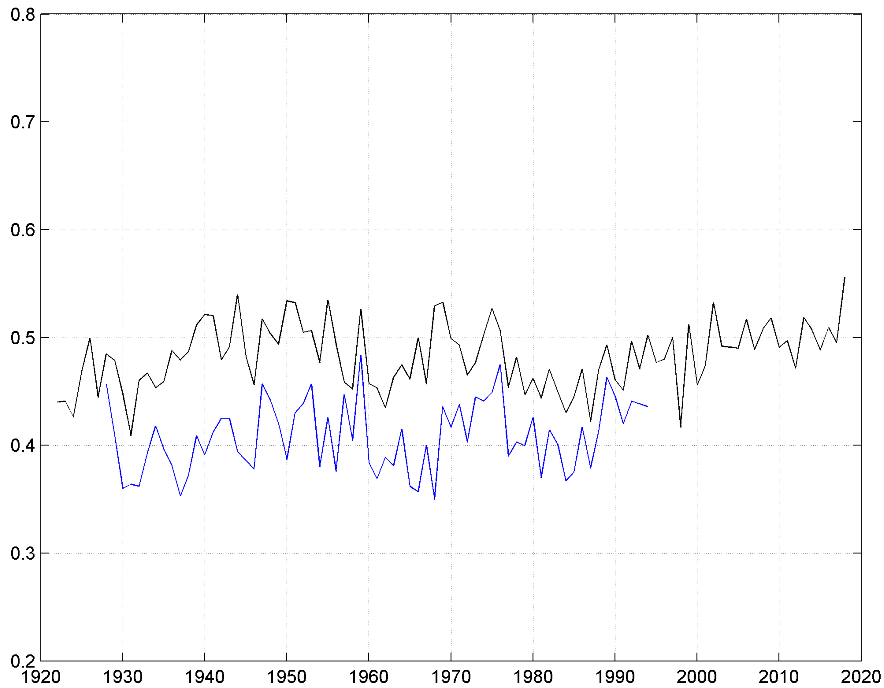

Figure 8.4 The relative global radiation for the Summer-half-year at Stockholm (black) and Wageningen (blue).

8.2.5 Influence from volcanic eruptions

During the almost one hundred years of observations of global radiation at Stockholm there have been two large volcanic eruptions; El Chichon, Mexico, in March and April 1982 and Pinatubo, Philippines, in June 1991. There have also been some smaller eruptions that may have some influence such as Agung, Indonesia, main eruption in March 1963, Fernandina Island, Galapagos, in June 1968 and Fuego, Guatemala, in 1974.

Can any effects from these eruptions be seen in the global radiation? All the volcanos mentioned are far away from Stockholm, so there is no tropospheric (low level atmospheric) volcanic debris arriving. If there is an effect from these eruptions it has to come from a stratospheric volcanic aerosol. A stratospheric aerosol will reduce the direct component but at the same time increase the diffuse. The overall effect is a reduction of the global radiation but it is not as large as one might expect. Therefore, looking at monthly or yearly values most of the variation seen in those data is connected to variations in the cloudiness (amount and optical thickness).

Selecting "relatively clear days" there is a small shift to lower values of the daily relative global radiation for about one year following the larger eruptions.

9 Conclusions

After one year of reading old material from the archive and trying to find out what have been done to the old measurements in the past, I know one thing for certain there is still a lot of work to be done. There has not been enough time to fully use all information regarding the calibration history of the series before 1983. There is probably also better ways to treat the oldest part of the series; i.e. before 1945 and there are still some loose ends for the years 1945-1951.

Compared to the originally published values the corrected series is probably a better estimate of the long-term variations.

There are no significant trends over the full period 1922-2018. Not for the individual months, not for seasons and not for the full year. For sub-periods of one or two decades there are clear ups and downs for the global radiation.

One positive and unplanned output from the project was the partly digitized and recalculated monthly values of sunshine duration for Stockholm. These values were found to correlate relatively well with the global radiation at least after 1951 when the instruments were co-located.

It is also been shown that the quality of the global irradiance measurements has improved over the years. This has been achieved by better instruments and improved data acquisition systems as well as improved calibration routines. It has also become much easier to detect measurement errors early, using modern quality assurance methods.

Another important upgrade was the introduction of ventilators and heaters that prevent frost to form on the dome. However, the overall guarantee for long-term high quality monitoring is dedicated and educated personal. They will fast detect and correct when something is wrong. This will give data series without long gaps and prevent extended periods when the calibration has drifted in an unknown way.

10 Afterword and acknowledgement

During this work my thoughts has often gone to those who struggled with the instruments and the monitoring in the past. A sincere “thank you” to all of them. Of course I cannot fully apprehend the pioneering work done by Aurén and Ångström. Their efforts have probably laid the cornerstone to the ambitious radiation measurements that still is done by SMHI. Seen from a far distance in time it seems that measuring global radiation has not always been the main focus for our predecessors. For example Aurén probably focused on illumination and ultraviolet radiation. And later generations improved the pyrheliometry and other areas within the radiation regime.

In the late 1970-ties the Swedish solar radiation network was in a relatively bad condition. The energy crisis a few years earlier had shown that sun, waves and wind might be an alternative to fossil energy even in Sweden. The government wanted SMHI to map the potential of these alternative sources for energy. It was soon detected that the quality of the available solar radiation data was not good enough. So Lars Dahlgren, an expert on measuring solar radiation, was appointed at SMHI to see what could be done. A few years later he was leading an upgrade of solar radiation monitoring network that in 1983 resulted in a new fully automated net of twelve stations all equipped with new pyranometers and pyrheliometers on suntrackers. This network has served us well providing good quality data. In 2007 the instruments and the technique could be regarded as old and a new upgrade was completed; now by Thomas Carlund. Unfortunately, due to lack of external funding SMHI had to reduce the number of suntrackers from twelve to three. But, there have been some additions of new sites to the net.

In last decades I have had help from students working a few weeks in the summer digitizing mainly hourly values of global radiation and sunshine duration. In particular I want to thank Camilla Andersson, who made a great and accurate job in 2005. In the summer of 2018 I had help from Martina Frid trying to understand the jump in the irradiation as SMHI shifted from one monitoring system to another in 1983. Discussion with her and Thomas Carlund who also participated in this work was most valuable.

I also want to express my gratitude to SMHI who has given me the opportunity to do this compilation, processing and scrutinizing of old data. Some of the work has been dedicated to dig into the archives to find the original data and also to find old publications related to the monitoring. Here I have had great help from my colleges Gunnar Larsson and Annika Nilsson. Everything has not been found in the archive of SMHI and the assistance I’ve got from Leo van Wely (former Kipp and Zonen) to understand to old CM2/3 instruments is most appreciated.

In only a few years the series of global radiation from Stockholm will be 100 year long. For many people this might just be a long row of numbers. But, for me it represents the struggle and efforts of many former colleges. There was so much time spent and often hard work to produce these seemingly few numbers long before I started to process them. I hope the data will be useful and valuable. And I sincerely hope that there will be others that will scrutinize, recalculate and improve the series over again because there is still lot of information in the raw data.

Weine Josefsson

Norrköping March 2019

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12 Appendix 1

12.1 Available raw data

Stansning av dygn och timvisa globalstrålningsdata för Stockholm													
bara dygnsvärden fram till sep 1945		x = Rådata				s = energivärden			M = endast månadsv				
ÅR	dygn	jan	feb	mar	apr	maj	jun	jul	aug	sep	okt	nov	dec
1922								M	M	M	M	M	M
1923	→	s	s	delar	s	s	delar	M	M	s	M	s	s
1924	→	s	s	s	s	s	s	s	s	delvis	s	s	s
1925		M	M	M	M	M	M	M	M	Mi	Mi	M	M
1926	→	M	M	M	s	s	s	s	s	s	s	s	s
1927	→	s	s	s	s	s	s	x	s	x	x	Mi	x
1928	→	x	x	x	x	x	x	x	x	x	Mi	Mi	x
1929	→	x	x	x	x	M	M	x	M	M	x	x	x
1930	→	x	x	x	M	M	M	M	x	x	x	x	M
1931	→	Mi	x	x	x	x	x	Mi	delvis	x	x	x	x
1932	→	x	x	x	x	x	x	x	x	x	x	x	x
1933	→	x	x	x	x	x	x	x	x	x	x	x	x
1934	→	x	x	x	√S	x	x	x	√S	x	√S	x	x
1935	→	x	x	x	x	x	x	√S	x	x	x	x	x
1936	→	x	x	x	x	x	x	x	x	x	x	x	x
1937	→	x	x	x	x	x	x	√S	x	x	x	x	x
1938	→	√S	x	x	x	x	x	x	x	x	x	x	x
1939	→	x	x	x	x	√S	x	x	x	x	x	x	x
1940	→	x	x	x	x	x	x	x	x	x	x	x	x
1941	→	x	x	x	x	x	x	x	x	x	x	x	x
1942	→	x	x	x	x	x	x	x	x	x	x	x	x
1943	→	x	x	x	x	x	x	x	x	x	x	x	x
1944	→	x	x	x	x	x	x	x	x	x	x	x	x
1945	→	x	x	x	x	x	x	x	x	x	x	x	x
1946	x	x	x	x	x	x	x	x	x	x	x	x	x
1947	x	x	x	x	x	x	x	x	x	x	x	x	x
1948	x		*ur funktion jan - juli*						x	x	x	x	x
1949	x	x	x	x	x	x	x	x	x	x	x	x	x
1950	x	x	x	x	x	x	x	x	x	x	x	x	x
1951	x	x	x	x	x	x	x	x	x	x	x	x	x
1952	x	x	x	x	x	x	x	x	x	x	x	x	x
1953	x	x	x	x	x	x	x	x	x	x	x	x	x
1954	x	x	x	x	x	x	x	x	x	x	x	x	x
1955	x	x	x	x	x	x	x	x	x	x	x	x	x
1956	x	x	x	x	x	x	x	x	x	x	x	x	x
1957	x	x	x	x	x	x	x	s_>X	s_>X	s_>X	s_>X	s_>X	s_>X
1958		x	x	x	x	x	x	x	x	x	x	x	x
1959		x	x	x	x	x	x	x	x	x	x	x	x
1960	x	x	x	x	x	x	x	x	x	x	x	x	x
1961	x	x	x	x	x	x	x	x	x	x	x	x	x
1962	x	x	x	x	x	x	x	x	x	x	x	x	x
1963	x	x	x	x	x	x	x	x	x	x	x	x	x
1964	x	x	x	x	x	x	x	x	x	x	x	x	x
1965	x	x	x	x	x	x	x	x	x	x	x	x	x
1966	x	x	x	x	x	x	x	x	x	x	x	x	x
1967	x	x	x	x	x	x	x	x	x	x	x	x	x
1968	x	x	x	x	x	x	x	x	x	x	x	x	x
1969	x	x	x	x	x	x	x	x	x	x	x	x	x
1970	x	x	x	x	x	x	x	x	x	x	x	x	x
1971	x	X	x	x	x	x	x	x	x	x	x	x	x
1972	x	X	x	x	x	x	x	x	x	x	x	x	x
1973	x	X	x	x	x	x	x	x	x	x	x	x	x
1974	x	X	x	x	x	x	x	x	x	x	x	x	x
1975	x	X	x	x	x	x	x	x	x	x	x	x	x
1976	x	X	x	x		x	x	x	x	x	x	x	x
1977	x	X	x	x	x	x	x	x	x	x	x	x	x
1978	x	X	x	x	x	x	x	x	x	x	x	x	x
1979	x	X	x	x	x	x	x	x	x	x	x	x	x
1980	x	x	x	x	x	x	x	x	x	x	x	x	x
1981	x	x	x	x	x	x	x	x	x	x	x	x	x
1982	x	x	x	x	x	x	x	x	x	x	x	x	x
1983		x	x	x	x	x	x	x	x	x	x	x	x
1983-2018	**data med minst timupplösning under denna period, redan digital, juli 1998 saknas**												

Figure A1.1 Checking list when digitizing global radiation data. Green indicates hourly values, yellow daily and for M only monthly values were found. Red indicates missing data. An x indicates that raw data exist and s only computed irradiance. From 1983 data were collected and thus available in digital form from start. Note that July 1998 is missing.

13 Appendix 2

13.1 Corrections applied to hourly values

Matlab® code used to correct hourly data for various instrument characteristics and for changes in calibrations.

```
% Weine Josefsson 2018 Sep 26-27      -program-  Correct.m --> correctg.m
% updates: ..
%
%          NOTE Correction FACTORS not change in responsivity
%
% Read yearly hourly data files Xxyyyy.txt -- includes global radiation ancillary data
% correct for known errors depending on instrument type
%
% write new output file CorrYYYY

clear;
yearin = input('Year to process: yyyy  ')

% Format -data infile  YYYY, MM, DD, JNR, HH, az, sole, RAW, Status, Tidtyp, CF, TempCal, SolhCal, Unit,
WRR, Site, InstType, temp, RelSS, PW, RH;
%              1  2 3  4  5  6  7  8  9   10  11  12   13  14  15  16   17   18  19  20
21

infile = ['//winfs/home/Weine.Josefsson/matlab/solhomo/timdata/Xx',num2str(yearin),'.txt'];
INDATA = load(infile);

YYYY= INDATA(:,1);    % yyyy 1945 -- 1983
MM= INDATA(:,2);      % mm 1-12
DD= INDATA(:,3);      % dd 1-31
DNR= INDATA(:,4);     % dnr 1-366
HH= INDATA(:,5);      % tim 1-24

AZ= INDATA(:,6);      % azimuth 0 -360
SH= INDATA(:,7);      % solar elevation -54 -- +54

RAW = INDATA(:,8);    % raw hourly values for global radiation
STATUS= INDATA(:,9);        % status meas value 1 observed, 2 other instr and 3 interpolated
Tidtyp= INDATA(:,10); % true solar time =0 (all data in Xxyyyy-files up to 1983)

CF = INDATA(:,11);    % original calibration factor (applied in the past)
TempCF = INDATA(:,12);      % temp at original calibration factor (usually unknown) default set to 20 C
SHCF = INDATA(:,13);  % solar elev at original calibration factor (usually unknown) default set to 40 degs
Unit = INDATA(:,14);  % factor to convert to Whm-2 based on applied hist. cal. factor
CWRR= INDATA(:,15);     % corr to get WRR (World Radiometric Reference)
```

```
SITE= INDATA(:,16);     % site (Stocksund =1; Fridhemsplan =2; Bromma =3)
Inst = INDATA(:,17);    % instrument type, affects the correction, see below

% Ancillary meteorological data in general missing data -99 or -999
TEMP = INDATA(:,18);            % hourly air-temperature in Stockholm degs C based on observations from
Obs.kullen and Bromma
SSdur = INDATA(:,19); % hourly rel. sunshine duration 0-1 from Vanadislunden, Fridhemsplan and Bromma.
PW= INDATA(:,20);       % hourly precipitable water (mm) from web-site
RH= INDATA(:,21);       % hourly relative humidity (%) based on observations at Bromma

% *****  initialize matrices *****
% get right size of matrices then fill with 1.000 , -999.0 or 0

irr=zeros(size(INDATA(:,1)))-999.0;

OFFcorr=zeros(size(INDATA(:,1)));

Tcorr=zeros(size(INDATA(:,1)))+1.000;
COScorr=zeros(size(INDATA(:,1)))+1.000;
AZcorr=zeros(size(INDATA(:,1)))+1.000;
LINcorr=zeros(size(INDATA(:,1)))+1.000;
CFcorr=zeros(size(INDATA(:,1)))+1.000;

Rcos = zeros(size(INDATA(:,1)))+1.000;
RcosNorm = zeros(size(INDATA(:,1)))+1.000;
Rcosiso = zeros(size(INDATA(:,1)))+1.000;

Fdir=zeros(size(INDATA(:,1)));
inc=zeros(size(INDATA(:,1)));
Gext =zeros(size(INDATA(:,1)));

%% ****************************************************************************************************
%% first approximation of irradiation
%% based on historical data this should nearly agree with published data converted to WRR and Whm-2
%% there may be a difference due to corretions (miscalculations etc) done by Weine
%%****************************************************************************************************

irr= RAW.*CF.*CWRR.*Unit;

% ***************************************************************************
% second an simplified approx of the extraterrestrial radiation hour by hour
% ***************************************************************************

I_0=1361;
```

```
F_avs = (1-(0.01672*cosd(0.9856*(DNR-4)))).^2;
Gext = (I_0*cosd(90-SH))./F_avs;
Gext(SH<=0)=0;


% ****************************************************************
% Establish the type of instrument that have been used every hour
%      ** CORRECT EACH INSTRUMENT TYPE SEPARATELY **
% ****************************************************************

% ** The Ångström pyranometer and the Aurén solarimeter were not used after 1945 October
% ** and the hourly data processed by this program for 1945 Oct up to Dec 1983

% ======================================================
%          The Ångström pyranometers
%   noted as instrument number type 1 in the files
%   only hours where irradiance (RAW) > 0 are corrected
% =======================================================

   indxA = find(Inst==1 & RAW>0);

%% ***************************************************
%% no OFFSET correction for Ångström pyranometer
%% ***************************************************

    OFFcorr(indxA) = 0;

%% *************************************************************************************
%% no linearity correction for Ångström pyranometer, small according to Ångström(1928) **
%% *************************************************************************************

  LINcorr(indxA) = 1.000;

%% ************************************************
%% temperature correction for Ångström pyranometer
%% ************************************************

  Tcorr(indxA) = 1.000;

%% *****************************************************************
%% cosine correction for Ångström pyranometer
%% Ångströms instrument #2 was initially equipped with a glass dome
%% the Ångström instrument #40 used from Feb 1931 was equipped with
%% a milk glass filter which had much worse cosine characteristics
%% *****************************************************************
```

```
  inc(indxA)=90- SH(indxA);

if YYYY(indxA) < 1931;
         Rcos(indxA) = -5.6877E-07.*inc(indxA).^3 + 4.504382E-05.*inc(indxA).^2 - 1.37379662E-03.*inc(indxA)
+ 1.006348945;
         RcosNorm(indxA)= -5.6877E-07.*(90-SHCF(indxA)).^3 + 4.504382E-05.*(90-SHCF(indxA)).^2 -
1.37379662E-03.*(90-SHCF(indxA)) + 1.006348945;
         Rcosiso(indxA)=1.000;
else
     Rcos(indxA)= - 6.341E-05.*inc(indxA).^2 + 1.5922E-04.*inc(indxA) + 9.9745352E-01;
     RcosNorm(indxA)=- 6.341E-05.*(90-SHCF(indxA)).^2 + 1.5922E-04.*(90-SHCF(indxA)) + 9.9745352E-01;
     Rcosiso(indxA)=1.000;
end

% estimated fraction direct solar (Fdir) from the sunshine duration
% a clear sky sdur=1 gives 80% direct and an overcast i.e. sdur=0 gives 0%

          Fdir(indxA) = 0.8.*SSdur(indxA);
% check to avoid erroneous values
          if Fdir(indxA)<0;
             Fdir(indxA)=0;
          elseif Fdir(indxA)>1
             Fdir(indxA)=1;
          end

% the final cosine correction factor is given by a linear combination

 COScorr(indxA) = 1.*(Fdir(indxA) ./(Rcos(indxA)./RcosNorm(indxA)) + (1-Fdir(indxA))./Rcosiso(indxA));

% *******************************************
% ***  No AZIMUTH Correction for Ångström ***
% *******************************************

AZcorr(indxA) = 1.0000;

% =========================================
%  The Kimball Eppley lightbulb pyranometer
%   noted as instrument type 2 in the files
% =========================================

indxE = find(Inst==2 & RAW>0);

%% ***************************************************
%% no OFFSET correction for Kimball Eppley pyranometer
%% ***************************************************

    OFFcorr(indxE) = 0;
```

```
%% ****************************************************************
%% no linearity correction for Kimball Eppley pyranometer found **
%% ****************************************************************

   LINcorr(indxE) = 1.000;

%% ***********************************************************************
%% temperature correction factor for Kimball Eppley pyranometer
%% (inverse of responsivity for temp)
%% temperature dep. of Eppley old pyranom normalised to an assumed
%% calibration temperature of 20 degs C (default)
%% or to temperature at the calibration TempCF
%% ***********************************************************************

         Tcorr(indxE) = 1./(1- 0.0011296.*(TEMP(indxE)-TempCF(indxE)));

%% *************************************************
%% cosine correction for Kimball Eppley pyranometer
%% *************************************************
  inc(indxE)=90- SH(indxE);

    Rcos(indxE)=-5.5957407E-08.*inc(indxE).^4 + 7.532164E-06.*inc(indxE).^3 - 2.985247E-04.*inc(indxE).^2 +
3.807779E-03.*inc(indxE) + 9.969447E-01;
    RcosNorm(indxE)=-5.5957407E-08.*(90-SHCF(indxE)).^4 + 7.532164E-06.*(90-SHCF(indxE)).^3 -
2.985247E-04.*(90-SHCF(indxE)).^2 + 3.807779E-03.*(90-SHCF(indxE)) + 9.969447E-01;
    Rcosiso(indxE)=1.000;

% estimated fraction direct solar (Fdir) from the sunshine duration
% a clear sky sdur=1 gives 80% direct and an overcast i.e. sdur=0 gives 0%

          Fdir(indxE) = 0.8.*SSdur(indxE);
% check to avoid erroneous values
          if Fdir(indxE)<0;
             Fdir(indxE)=0;
          elseif Fdir(indxE)>1
             Fdir(indxE)=1;
          end

% the final cosine correction factor is given by a linear combination

    COScorr(indxE) = 1.*(Fdir(indxE) ./(Rcos(indxE)./RcosNorm(indxE)) + (1-Fdir(indxE))./Rcosiso(indxE));

% ********************************************************
% ***  No AZIMUTH Correction found for Kimball Eppley ***
% ********************************************************
```

```
        AZcorr(indxE) = 1.0000;

% ================================================
%  The Kipp and Zonen pyranometer type CM2 and 3
%   noted as instrument type 3 in the files
% ================================================

indxMG = find(Inst==3 & RAW>0);

%% ***********************************************************
%% OFFSET correction Kipp and Zonen pyranometer type CM2 and 3
%% assumed to be similar to CM5 unventilated last year 1972
%% all instruments were UNVENTILATED
%%  ad hoc model that produces Offset between 0 and about 6 watts
%% assumption that the calibration is done at clear sky with an uncorrected offset of
%% about 6 watt. This gives a calibration factor approximately 1% too high
%% Thus a factor of 0.99 should be applied to all values after offset correction
%%  for UNVENTILATED CM 2, 3 and 5
%%
%%  for VENTILATED  see comment for CM5 below
%%
%%    NOTE: OFFSETS DEFINED AS ABOVE AND FORMAILSED AS BELOW SHOULD BE SUBTRACTED
%% ***********************************************************
 if YYYY(indxMG)<1973
      OFFcorr(indxMG)= -6.*SSdur(indxMG);
      CFcorr(indxMG)= 0.99;
 end
 if YYYY(indxMG)>1972
       OFFcorr(indxMG)= 2.5+ 2.*(1-SSdur(indxMG));
       CFcorr(indxMG)= 1.005;
 end

%% **********************************************************************
%% linearity correction for Kipp and Zonen pyranometer type CM2 and 3
%%      normalized at 650 Watt m-2
%% **********************************************************************

   R5lin(indxMG)= 2.47668998E-14.*irr(indxMG).^4 - 5.00194250E-11.*irr(indxMG).^3 + 2.17803030E-
08.*irr(indxMG).^2 - 1.06536519E-05.*irr(indxMG) + 1.00411888E+00;
   R5lincal(indxMG)= 2.47668998E-14.*650.^4 - 5.00194250E-11.*650.^3 + 2.17803030E-08.*650.^2 -
1.06536519E-05.*650 + 1.00411888E+00;
   LINcorr(indxMG) = 1./(R5lin(indxMG)./R5lincal(indxMG));

%% ***********************************************************************
%% temperature correction factor for Kipp and Zonen pyranometer type CM2 and 3
%% (inverse of change in responsivity)
%% temperature dep. of CM2 and CM3 pyranom normalised to an assumed
```

```
%% calibration temperature of 20 degs C (default)
%% if the temperature of the calibration TempCF is known an adjustment
%% is done
%% ************************************************************************

  Tcorr(indxMG) =1./ (1.04166667E-09.*TEMP(indxMG).^4 + 5.23989899E-08.*TEMP(indxMG).^3 - 8.28598485E-06.*TEMP(indxMG).^2 - 6.83378427E-04.*TEMP(indxMG) + 1.01659145E+00);
  Tcorr(indxMG) = Tcorr(indxMG).*(1.04166667E-09.*TempCF(indxMG).^4 + 5.23989899E-08.*TempCF(indxMG).^3 - 8.28598485E-06.*TempCF(indxMG).^2 - 6.83378427E-04.*TempCF(indxMG) + 1.01659145E+00);
%% *******************************************************************
%% cosine correction for Kipp and Zonen pyranometer type CM2 and 3
%% is assumed to be like that of a CM5-instrument
%% *******************************************************************

  inc(indxMG)=90- SH(indxMG);

    Rcos(indxMG)= -5.594406E-09.*inc(indxMG).^4 + 7.267547E-07.*inc(indxMG).^3 - 3.687840E-05.*inc(indxMG).^2 + 1.843370E-04.*inc(indxMG) + 9.994250E-01;
    RcosNorm(indxMG)= -5.594406E-09.*(90-SHCF(indxMG)).^4 + 7.267547E-07.*(90-SHCF(indxMG)).^3 - 3.687840E-05.*(90-SHCF(indxMG)).^2 + 1.843370E-04.*(90-SHCF(indxMG)) + 9.994250E-01;
    Rcosiso(indxMG)= 1./0.9995;

% estimated fraction direct solar (Fdir) from the sunshine duration
% a clear sky sdur=1 gives 80% direct and an overcast i.e. sdur=0 gives 0%

        Fdir(indxMG) = 0.8.*SSdur(indxMG);
% check to avoid erroneous values
        if Fdir(indxMG)<0;
          Fdir(indxMG)=0;
        elseif Fdir(indxMG)>1
          Fdir(indxMG)=1;
        end

% the final cosine correction factor is given by a linear combination
     COScorr(indxMG) = 1.*(Fdir(indxMG) ./(Rcos(indxMG)./RcosNorm(indxMG)) + (1-Fdir(indxMG))./Rcosiso(indxMG));

% ******************************************************************************
% ***  AZIMUTH Correction only for Kipp a Zonen CM2 (MG) CM3 (MG) and CM5 ***
% ***       values based on data from IEA(1984)                      ***
% ******************************************************************************

   V_y =[1.4 1.36 1.3 1.21 1.18 1.15 1.11 1.076 1.06 1.032 1.025 1.02 1.015 1.01 1]';
   V_x = [90 85 80 75 73 72 70  65 60 50 40 30 20 10 0]';

%  values by Cubic spline interpolation
   xq=0:90;
```

```
    vq = interp1(V_x,V_y,xq,'spline');
    PP  = csapi(xq,vq);
%% azimuth respcorrection for direct component of global
    AZcorr(indxMG) = 1+(0.35.*2.5.*((fnval(PP,(90 - SH(indxMG))))-1)).*(sind((AZ(indxMG)-180)/2).^2);
%% rough azimuth FACTOR-correction for globalradiation only for hours with sunshine and only 80% by
reducing the fraction larger than one.

    AZcorr(indxMG) = 1./(1+ (AZcorr(indxMG)-1).*0.8.*SSdur(indxMG));



% ==============================================
%  The Kipp and Zonen pyranometer type CM5
%   noted as instrument type 4 in the files
%  only hours with irradiance>0 are corrected
% ==============================================

indxCM5 = find(Inst==4 & RAW>0);

%% ************************************************************
%%  OFFSET correction Kipp and Zonen pyranometer type CM5
%%  until 1972 UN-ventilated correction
%%  from  1973 VENTILATED correction
%%  assumed to be part of calibration for irr >600
%%
%% UNVENTILATED
%%  ad hoc model that produces Offset between 0 and about -6 watts
%% assumption that the calibration is done at clear sky with an uncorrected offset of
%% about -6 watt. This gives a calibration factor approximately 1% too high
%% Thus a factor of 0.99 should be applied to all values after offset correction
%%
%% VENTILATED CM 5
%%  ad hoc model that produces Offset between about +2 and +4 watts
%% assumption that the calibration is done at clear sky with an uncorrected offset of
%% about 3 watt. This gives a calibration factor approximately 0.5% too low
%% Thus a factor of 1.005 should be applied to all values after offset correction
%%
%%    NOTE: OFFSETS DEFINED AS ABOVE SHOULD BE SUBTRACTED
%% ******************************************************************************************
    if YYYY(indxCM5)<1973
        OFFcorr(indxCM5)= -6.*SSdur(indxCM5);
        CFcorr(indxCM5)= 0.99;
    end

    if YYYY(indxCM5)>1972
        OFFcorr(indxCM5)= 2.5+ 2.*(1-SSdur(indxCM5));
        CFcorr(indxCM5)= 1.005;
```

```
   end


%% ************************************************************************
%%  linearity correction for Kipp and Zonen pyranometer type CM5
%%  normalised assuming calibration irradiance 650 Wm-2
%% ************************************************************************


  if  irr(indxCM5)==0
      LINcorr(indxCM5) = 1.000;
  else
    R5lin(indxCM5)= 2.47668998E-14.*irr(indxCM5).^4 - 5.00194250E-11.*irr(indxCM5).^3 + 2.17803030E-08.*irr(indxCM5).^2 - 1.06536519E-05.*irr(indxCM5) + 1.00411888E+00;
    R5lincal(indxCM5)= 2.47668998E-14.*650.^4 - 5.00194250E-11.*650.^3 + 2.17803030E-08.*650.^2 - 1.06536519E-05.*650 + 1.00411888E+00;
    LINcorr(indxCM5) = 1./(R5lin(indxCM5)./R5lincal(indxCM5));
  end
%% ************************************************************************
%% temperature correction factor for Kipp and Zonen pyranometer type CM5
%% (inverse of change in responsivity)
%% temperature dep. of CM5 pyranom normalised to default 20 degs C
%% or to temperature at the calibration TempCF
%% ************************************************************************


   Tcorr(indxCM5) =1./ (1.04166667E-09.*TEMP(indxCM5).^4 + 5.23989899E-08.*TEMP(indxCM5).^3 - 8.28598485E-06.*TEMP(indxCM5).^2 - 6.83378427E-04.*TEMP(indxCM5) + 1.01659145E+00);
   Tcorr(indxCM5) =Tcorr(indxCM5).* (1.04166667E-09.*TempCF(indxCM5).^4 + 5.23989899E-08.*TempCF(indxCM5).^3 - 8.28598485E-06.*TempCF(indxCM5).^2 - 6.83378427E-04.*TempCF(indxCM5) + 1.01659145E+00);


%% ********************************************************************
%% cosine correction for Kipp and Zonen pyranometer type CM5
%%  first responsivity  then convert to factor
%% ********************************************************************


   inc(indxCM5)=90- SH(indxCM5);


     Rcos(indxCM5)= -5.594406E-09.*inc(indxCM5).^4 + 7.267547E-07.*inc(indxCM5).^3 - 3.687840E-05.*inc(indxCM5).^2 + 1.843370E-04.*inc(indxCM5) + 9.994250E-01;
     RcosNorm(indxCM5)= -5.594406E-09.*(90-SHCF(indxCM5)).^4 + 7.267547E-07.*(90-SHCF(indxCM5)).^3 - 3.687840E-05.*(90-SHCF(indxCM5)).^2 + 1.843370E-04.*(90-SHCF(indxCM5)) + 9.994250E-01;
     Rcosiso(indxCM5)= 1./0.9995;


% estimated fraction direct solar (Fdir) from the sunshine duration
% a clear sky sdur=1 gives 80% direct and an overcast i.e. sdur=0 gives 0%


           Fdir(indxCM5) = 0.8.*SSdur(indxCM5);
% check to avoid erroneous values
           if Fdir(indxCM5)<0;
              Fdir(indxCM5)=0;
```

```
            elseif Fdir(indxCM5)>1
               Fdir(indxCM5)=1;
            end

% the final cosine correction factor is given by a linear combination
      COScorr(indxCM5) = 1.*(Fdir(indxCM5) ./(Rcos(indxCM5)./RcosNorm(indxCM5)) + (1-
Fdir(indxCM5))./Rcosiso(indxCM5));
%*******************************************************************************************
% ***  AZIMUTH responsivity-correction only for Kipp a Zonen CM2 (MG) CM3 (MG) and CM5 ***
% ***       values based on data from IEA(1984)                              ***
% ******************************************************************************************

V_y =[1.4 1.36 1.3 1.21 1.18 1.15 1.11 1.076 1.06 1.032 1.025 1.02 1.015 1.01 1]';
V_x = [90 85 80 75 73 72 70  65 60 50 40 30 20 10 0]';

%  values by Cubic spline interpolation

xq=0:90;
vq = interp1(V_x,V_y,xq,'spline');
PP  = csapi(xq,vq);

  AZcorr(indxCM5) = 1+(0.35.*2.5.*((fnval(PP,(90 - SH(indxCM5))))-1)).*(sind((AZ(indxCM5)-180)/2).^2);

  %% rough azimuth correction-FACTOR for globalradiation only for hours with sunshine and only 80%
   AZcorr(indxCM5) = 1./(1+ (AZcorr(indxCM5)-1).*0.8.*SSdur(indxCM5));

% =============================================
%  The Kipp and Zonen pyranometer type CM10/11
%   noted as instrument type 5 in the files
%  only hours with irradiance>0 are corrected
% =============================================

indxCM10 = find(Inst==5 & RAW>0);

%% *************************************************************
%%  OFFSET correction Kipp and Zonen pyranometer type CM10
%% *************************************************************

    OFFcorr(indxCM10) = 0;

%% ***********************************************************************
%%  linearity correction for Kipp and Zonen pyranometer type CM10
%% ***********************************************************************

  if  irr(indxCM10)==0
      LINcorr(indxCM10) = 1.000;
```

```
  else
      LINcorr(indxCM10) =1.000;
  end

%% ***********************************************************************
%% temperature correction factor for Kipp and Zonen pyranometer type CM10
%% (inverse of change in responsivity)
%% temperature dep. of CM10 pyranom normalised to default 20 degs C
%% or to temperature at the calibration TempCF
%% ***********************************************************************

% temp dep. of CM11 #800080 normalised to 20 degs.

  Tcorr(indxCM10) =1./ (6.5843621E-10.*TEMP(indxCM10).^5 - 4.6913580E-08.*TEMP(indxCM10).^4 +
1.2921811E-06.*TEMP(indxCM10).^3 - 3.0761317E-05.*TEMP(indxCM10).^2 - 2.8456790E-
04.*TEMP(indxCM10) + 1.0130576E+00);

%% *****************************************************************
%% cosine correction for Kipp and Zonen pyranometer type CM10
%%  first responsivity  then convert to factor
%% *****************************************************************

  inc(indxCM10)=90- SH(indxCM10);

    Rcos(indxCM10)= 1.069093E-11.*inc(indxCM10).^6 - 2.471120E-09.*inc(indxCM10).^5 + 2.091376E-
07.*inc(indxCM10).^4 - 7.972859E-06.*inc(indxCM10).^3 + 1.369437E-04.*inc(indxCM10).^2 - 8.054556E-
04.*inc(indxCM10) + 1.000099E+00;

    RcosNorm(indxCM10)= 1.069093E-11.*(90-SHCF(indxCM10)).^6 - 2.471120E-09.*(90-SHCF(indxCM10)).^5
+ 2.091376E-07.*(90-SHCF(indxCM10)).^4 - 7.972859E-06.*(90-SHCF(indxCM10)).^3 + 1.369437E-04.*(90-
SHCF(indxCM10)).^2 - 8.054556E-04.*(90-SHCF(indxCM10)) + 1.000099E+00;

    Rcosiso(indxCM10)= 1./0.9966;

% estimated fraction direct solar (Fdir) from the sunshine duration
% a clear sky sdur=1 gives 80% direct and an overcast i.e. sdur=0 gives 0%

          Fdir(indxCM10) = 0.8.*SSdur(indxCM10);
% check to avoid erroneous values
          if Fdir(indxCM10)<0;
             Fdir(indxCM10)=0;
          elseif Fdir(indxCM10)>1
             Fdir(indxCM10)=1;
          end

% the final cosine correction factor is given by a linear combination
     COScorr(indxCM10) = 1.*(Fdir(indxCM10) ./(Rcos(indxCM10)./RcosNorm(indxCM10)) + (1-
Fdir(indxCM10))./Rcosiso(indxCM10));

% *********************************************************
% ***  no AZIMUTH Correction for Kipp a Zonen CM10/11   ***
```

```
% ***        based on data from IEA(1984)            ***
% ***********************************************************

  AZcorr(indxCM10) = 1.0000;



%% *************************************************************
%% For some periods the applied instrument constant factor has been in error
%% here an adjustment is done
%% NOTE: that CFcorr is adjusted in the offset correction so
%%       there might be a correction on the correction
%%%***************************************************************

%% period 29 Aug 1966 till 31 Oct 1969 a correction of 5%
%% the new instr 662560 seems to be in error when calibrated

indxCF1 = find(YYYY==1966 & DNR>240);
CFcorr(indxCF1)= 0.964.*CFcorr(indxCF1);

indxCF2 = find(YYYY==1967);
CFcorr(indxCF2)= 0.964.*CFcorr(indxCF2);

indxCF3 = find(YYYY==1968);
CFcorr(indxCF3)= 0.964.*CFcorr(indxCF3);

indxCF4 = find(YYYY==1969 & DNR<305);
CFcorr(indxCF4)= 0.964.*CFcorr(indxCF4);

%%% At Bromma period 1 Sept 1977 till 31 Dec 1983 (here is Bromma 1983 not KTH) a correction of 4.7%
%%% the use of reference pyranomenter is assumed to cause an  error when
%%% the calibration is transferred

indxCF5 = find(YYYY==1977 & DNR>243);
CFcorr(indxCF5)= 0.98.*CFcorr(indxCF5);

indxCF6 = find(YYYY==1978);
CFcorr(indxCF6)= 0.98.*CFcorr(indxCF6);

indxCF7 = find(YYYY==1979);
CFcorr(indxCF7)= 0.98.*CFcorr(indxCF7);

indxCF8 = find(YYYY==1980);
CFcorr(indxCF8)= 0.98.*CFcorr(indxCF8);

indxCF90 = find(YYYY==1981 & DNR<244);
CFcorr(indxCF90)= 0.98.*CFcorr(indxCF90);
```

```
indxCF91 = find(YYYY==1981 & DNR>243);
CFcorr(indxCF91)= 0.953.*CFcorr(indxCF91);

indxCF10 = find(YYYY==1982);
CFcorr(indxCF10)= 0.953.*CFcorr(indxCF10);

indxCF11 = find(YYYY==1983);
CFcorr(indxCF11)= 0.953.*CFcorr(indxCF11);

%============================================
%
%    ESTIMATE OF CORRECTED IRRADIATION
%
%============================================
  IRRc = zeros(size(INDATA(:,1)))-999.0;

 IRRc = CFcorr.*(irr-OFFcorr).*Tcorr.*COScorr.*AZcorr.*LINcorr;

if IRRc <0
        IRRc = 0;
end

% add columns to the matrix with corrections

NEW =[INDATA,irr,OFFcorr,CFcorr,Tcorr,COScorr,AZcorr, LINcorr,IRRc,Gext];

% save NEWFILE NEW -ascii;

utfilen = ['//winfs/home/Weine.Josefsson/matlab/solhomo/timdata/Corr',num2str(yearin),'.txt'];
fp=fopen(utfilen,'w+');
fprintf(fp, '%5.0f \t %3.0f \t %3.0f \t %4.0f \t %3.0f \t %5.1f \t %5.1f \t %6.2f \t %3.0f \t %3.0f\t %6.2f \t %5.1f \t
%5.1f \t %6.2f \t %6.3f \t %3.0f \t %3.0f \t %5.1f \t %7.1f \t %6.3f \t %6.1f \t %6.1f \t %6.1f \t %6.3f \t %6.3f \t
%6.3f \t %6.3f \t %6.3f \t %6.1f \t %7.1f \n', NEW');
fclose(fp);
```

14 Appendix 3

14.1 Sunshine duration at Stockholm

Unfortunately, there has not been any revision or thoroughly study of the sunshine duration measured in Stockholm. Therefore, the author of this report had to compile and control these data as part of the present study of global irradiance. Due to limited time this work has not been done as good as one would wish.

The observations used here started in 1908 but there is an older series from Stockholm-Skansen that started a few years earlier (late 1904). But checking the overlap period clearly shows that something was not as good as one would hope. It was noted by Westman (1917) that the sensitivity of the heliograph probably was lower than later units. Using a simple correction by month it is possible to convert the Skansen data to later observations.

A similar problem is evident as the instrument used at Stockholm-Vanadislunden was for a long time period a modified Jordan photographic sunshine recorder here called Hamberg instrument. It seems that the sensitivity of this specific instrument was similar to the Campbell-Stokes heliograph and thus the observations are comparable without any correction.

The observations by the heliographs were processed in detail during the early period. As already mentioned they were aware of and also measured the sensitivity of the heliographs using pyrheliometers. They also calculated the relative sunshine and consequently knew about the importance of the problem that an obscuring horizon could cause. This caused a problem for the years 1928 and 1929 in this report. The original records could not be found in the archives and therefore the values had to be taken from published monthly values in the Yearbook (the yearly compilation). But in the archive there was a handwritten compilation of monthly values that differed from those published.

A first guess is that the published values should be the best as those should have been selected in close connection to the measurements. However, taking a look at the individual monthly values also published in the Yearbook ('Månadsöversikten') as the average sunshine per day of each month this number multiplied by the number of days in the month didn't agree with the monthly sum found in the yearly compilation.

Checking this for all months for the period 1924 to 1934 revealed that this discrepancy only existed for the years 1928 and 1929. Taking the ratio of the monthly value based on 'Månadsöversikten' and 'the yearly compilation' revealed an interesting pattern. It seemed that there had been a monthly correction applied to the original values. At first this "correction" was not clear. But, almost the same numbers (times 100) was found on page 15 in Ångström (1928). There the numbers represent the time in percent of the astronomical time of sunshine as recorded by the Hamberg sunshine recorder during clear days at Stockholm.

Multiplying the recorded time by these numbers for clear days will thus give the day-length (sunrise to sunset). This would for clear days correct for the local terrestrial horizon but it would also add the time when the direct solar irradiance is below the sensitivity of the instrument. And apply these factors for days with broken cloud cover would also give too high values if our definition of sunshine duration is based on e.g. 120 watt/m^2 direct irradiance. Therefore, the decision was to remove the factor from the monthly values to get comparable values.

Table A3.1 Compilation of corrected monthly values of sunshine duration (hours) for Stockholm 1904-2018. See text for details. The first years are changed to agree with the following years using the overlap years. Other eventual corrections are discussed in the text.

1904									182.5		70.1		
1905	78.8	103.7	58.6	176.5	282.1	348.1	280.5	214.8	151.1	56.4	34.6	74.0	1859.1
1906	45.6	31.0	134.8	202.0	259.3	312.2	372.8	269.3	146.3	117.3	38.5	19.2	1948.1
1907	62.5	86.1	176.4	132.0	212.0	198.9	202.1	189.7	184.8	52.5	18.1	6.8	1521.8
1908	60.2	64.2	141.8	200.3	311.5	344.2	336.3	246.0	184.6	100.8	55.2	17.4	2062.5
1909	23.4	85.6	36.3	198.4	225.2	286.0	279.9	232.7	146.1	74.6	67.7	16.1	1672.0
1910	24.5	26.7	144.9	216.5	303.9	328.7	202.5	217.2	103.5	111.8	33.9	25.6	1739.7
1911	63.2	60.3	141.3	155.6	324.9	223.7	289.6	278.6	152.2	99.8	29.4	5.6	1824.2
1912	38.9	35.6	69.4	242.1	145.8	229.2	276.8	101.5	142.8	50.5	35.9	7.8	1376.3
1913	30.4	72.9	151.3	201.1	286.7	248.1	163.7	151.9	163.1	85.8	18.7	26.4	1600.1
1914	35.6	51.9	74.2	228.8	259.1	325.4	355.7	233.7	194.6	74.9	19.2	6.8	1859.9
1915	11.1	27.4	127.0	210.9	259.4	268.3	156.8	149.7	163.8	45.8	13.4	14.5	1448.1
1916	11.0	45.2	65.2	164.0	252.9	212.4	216.7	173.5	149.2	71.7	23.5	1.8	1387.1
1917	32.8	112.6	122.2	145.1	345.7	371.9	283.6	254.4	148.7	74.5	34.8	13.7	1940.0
1918	11.7	75.4	179.1	156.6	385.0	279.9	286.9	183.2	154.3	59.3	45.5	5.2	1822.1
1919	11.0	102.8	123.0	169.4	327.6	215.0	298.8	195.1	188.4	99.5	41.2	22.2	1794.0
1920	25.6	103.5	198.9	121.8	248.5	333.5	264.6	138.4	130.2	102.3	16.6	9.8	1693.7
1921	15.9	76.1	171.0	268.4	384.6	298.8	312.3	237.7	209.8	147.6	31.7	6.8	2160.7
1922	12.5	29.7	105.3	164.6	271.4	317.2	256.6	192.4	146.7	119.3	45.9	3.9	1665.5
1923	32.1	46.5	121.4	201.4	201.1	192.7	306.6	148.5	139.7	80.0	57.5	33.0	1560.5
1924	25.1	51.3	113.6	192.3	209.5	211.3	310.0	269.7	162.3	84.6	21.4	16.2	1667.3
1925	58.5	59.1	128.3	241.2	249.9	318.2	316.1	238.4	161.0	122.1	44.6	35.1	1972.5
1926	15.5	39.9	169.4	200.1	171.6	330.9	368	269	154	120	46	40	1924.4
1927	15	67	138	138	195	230	257	224	190	107	46	29	1636.0
1928	37.2	101.5	204.6	168.0	285.2	195.0	285.2	161.2	162.0	86.8	27.0	18.6	1732.3
1929	31.0	39.2	158.1	162.0	254.2	255.0	254.2	198.4	114.0	52.7	24.0	18.6	1561.4
1930	36	102	189	204	283	299	302	225	96	79	57	8	1880.0
1931	9	17	198	144	195	246	189	214	135	140	18	40	1545.0

1932	40	113	149	165	257	288	322	239	189	105	60	16	1943.0
1933	28	59	134	217	241	353	296	230	158	76	32	40	1864.0
1934	39	94	51	204	315	342	220	276	196	90	36	0	1863.0
1935	26	62	176	185	240	299	266	202	116	75	18	3	1668.0
1936	19	72	123	156	293	391	274	211	231	66	32	23	1891.0
1937	28	53	93	195	291	312	276	236	159	102	27	16	1788.0
1938	31	87	152	210	288	282	214	260	201	84	57	6	1872.0
1939	17	49	65	164	293	259	290	244	202.5	149.4	52.2	15.9	1801.0
1940	34.8	48.3	95.1	245.3	308.4	391.3	307.6	215.3	176.9	67.3	54.9	22.2	1967.4
1941	66.5	27.9	102.5	283.8	391.2	321.7	333.3	196.5	168.3	122.5	35.0	18.7	2067.9
1942	10.1	81.5	212.3	255.9	244.5	236.6	299.2	254.2	201.6	73.3	46.7	17.7	1933.6
1943	9.5	85.7	191.1	198.8	339.1	293.5	288.6	224.8	148.4	83.6	22.5	51.2	1936.8
1944	49.6	81.2	118.2	201.4	238.8	213.0	351.8	334.4	148.1	89.8	31.0	32.2	1889.5
1945	31.7	48.0	151.3	170.1	270.8	304.8	258	211	189.5	99.4	37.6	11.7	1783.9
1946	60.1	49.6	130.3	167.5	283.9	255.7	362.7	201.9	143.1	139.2	28.4	6.8	1829.2
1947	19.9	69.1	90.9	177.8	354.7	308.3	304.9	342.8	206.7	138.4	20.7	19.8	2054.0
1948	13.8	87.1	168.7	200.3	272.7	294.7	326.9	219.3	130.2	127.4	68.3	33.3	1942.7
1949	47.2	100.4	172.7	185.2	303.0	226.3	300.6	248.5	158.1	126.5	14.3	17.3	1900.1
1950	34.3	52.3	190.4	145.7	278.5	281.2	257.7	301.7	127.9	110.4	29.0	17.3	1826.4
1951	16.4	10.2	117.8	143.0	277.8	280.5	325.9	219.6	171.8	118.8	32.7	36.3	1750.8
1952	30.0	65.2	190.7	216.1	259.5	290.6	281.7	231.4	180.0	17.1	14.4	19.4	1796.1
1953	67.9	61.1	186.5	243.9	266.7	337.2	249.0	219.7	171.8	54.2	56.4	18.0	1932.4
1954	32.1	60.4	92.7	190.6	255.8	276.0	237.1	220.1	176.5	102.4	33.6	30.1	1707.4
1955	38.3	63.3	134.2	234.1	222.9	324.4	385.2	340.9	141.7	109.4	70.2	22.2	2086.8
1956	42.1	65.9	207.6	183.7	346.8	239.6	295.1	191.7	200.4	123.1	51.7	42.6	1990.3
1957	52.6	44.4	115.2	212.1	261.1	255.3	248.6	228.2	94.7	79.4	55.8	34.1	1681.5
1958	42.8	90.7	158.1	186.0	234.5	263.8	278.2	175	164.1	107.8	47.8	35.2	1784.0
1959	55.2	123.8	168.8	201.4	295.0	315.4	371.7	307.8	216.0	109.2	25.9	2.9	2193.1
1960	31.0	96.6	183.6	237.6	265.0	313.2	205.8	155.7	187.0	62.2	7.9	2.2	1747.8
1961	51.8	74.8	184.5	280.3	204.1	296.7	188.4	215.5	176.6	110.7	64.9	46.8	1895.1
1962	50.8	65.3	180.6	201.3	176.2	302.1	229.7	195.7	138.0	125.0	38.8	44.8	1748.3
1963	62.0	59.5	186.5	144.2	336.6	270.9	290.4	168.8	198.1	93.8	42.7	50.6	1904.1

1964	79.1	47.0	172.2	208.5	320.4	276.8	263.7	184.0	171.7	111.5	55.2	30.2	1920.3
1965	36.0	77.1	168.2	137.9	352.7	235.2	237.1	201.6	114.0	135.5	87.5	32.1	1814.9
1966	30.8	66.1	100.6	155.7	276.5	344.7	307.2	237.2	163.1	72.6	37.8	3.9	1796.2
1967	46.0	47.5	126.5	195.6	203.2	297.2	316.8	217.5	134.3	63.7	58.7	47.0	1754.0
1968	48.9	88.0	133.6	266.1	228.6	375.8	289.5	281.8	161.1	112.4	28.7	21.0	2035.5
1969	6.9	32.6	230.8	183.4	238.7	385.2	345.8	317.2	200.2	108.8	63.9	16.9	2130.4
1970	59.1	113.6	54.3	96.5	255.4	404.3	212.9	269.8	155.2	64.0	41.2	36.2	1762.5
1971	45.4	60.1	89.7	190.6	304.2	299.1	281.6	252.9	139.6	125.2	82.8	56.9	1928.1
1972	18.4	39.9	160.4	140.6	268.0	289.5	298.7	192.4	141.8	100.1	62.9	26.4	1739.1
1973	26.6	82.8	153.9	160.6	295.9	322.7	311.3	282.4	144.0	160.8	90.2	38.1	2069.3
1974	39.7	60.3	179.4	255.4	346.9	329.7	202.2	303.8	174.1	34.4	17.6	29.6	1973.1
1975	36.6	131.9	143.0	201.8	288.7	371.0	340.8	274.4	165.8	115.5	25.1	59.6	2154.2
1976	54.1	61.6	141.6	180.4	253.5	316.0	293.1	316.5	179.4	63.1	47.8	13.4	1920.5
1977	22.2	37.8	152.6	155.2	267.0	289.6	190.1	219.6	175.9	62.0	53.5	30.4	1655.9
1978	51.9	82.4	90.4	205.9	303.1	315.7	226.9	225.7	123.0	122.5	63.7	35.7	1846.9
1979	20.8	105.7	90.1	118.7	241.3	336.7	154.3	229.6	172.4	113.2	20.6	33.5	1636.9
1980	30.4	85.1	155.3	188.5	266.4	311.9	272.0	137.7	88.6	101.6	71.0	17.1	1725.6
1981	50.1	47.7	133.4	236.5	320.7	174.8	229.0	192.1	143.1	97.1	48.8	23.4	1696.7
1982	55.9	74.0	112.0	188.2	253.8	238.5	334.7	234.5	159.4	58.5	73.9	26.9	1810.3
1983	24	118	82	109	228	268	301	284	126	99	75	29	1743
1984	44	43	128	210	258	220	191	202	99	70	41	23	1529
1985	37	106	81	172	306	233	231	172	177	127	39	42	1723
1986	22.2	85.3	92.2	133.4	316.3	306.6	258.6	125.4	189.7	89.1	46.7	21.6	1687.1
1987	80.2	111.8	175.1	206.1	190.7	126.9	275.8	134.4	154.6	90.9	47	35.1	1628.5
1988	5.7	11.1	85.7	190.8	337.8	232.6	238.9	166.4	190.9	136.8	93.4	61.3	1751.4
1989	55.6	87.1	79.1	168.6	329.4	301.9	284.3	190.2	177.8	98.9	55.6	36.4	1864.8
1990	26.6	35.5	168.3	232.6	303.5	286.1	192.9	221.2	76.3	91.5	57.2	35	1726.8
1991	56.6	50.7	61.8	211.4	194.6	173.9	306.2	212	196.2	82.4	24	34.1	1603.8
1992	73.4	65.4	90.5	113.8	358.1	344.9	267.8	178.4	136.6	62.1	34	32.1	1757.1
1993	50.6	74.1	125.8	226.3	333	250.8	184.6	166.8	157.9	94.8	9	24.5	1698.1
1994	43.1	96	130.4	196.4	325	275.3	423.9	190.4	120	117.3	72.7	29.5	2019.9
1995	44.7	80.1	87.2	179.1	245.9	264.2	305.3	307.8	125.9	117.4	57.2	73.2	1888.1

1996	37.4	99.1	142.8	253.4	217.4	218.6	232.7	302.1	175.5	91.5	40.5	55.9	1866.9
1997	78.3	83.7	203	229	261.1	290.7	326.9	280.2	160.1	104.4	35.9	7	2060.4
1998	28.7	40.3	128	131.2	283.5	157	201	165.6	138	85.5	38	20.2	1417
1999	36.3	80.9	82.9	175.4	290	320	334.6	261	181.6	85.9	64.9	37.6	1950.9
2000	68.3	91.2	220.2	168.6	262.9	261.8	145.5	220	228.8	42.3	7.9	25.8	1743.4
2001	39.1	112.8	149.2	175.2	263.1	281.9	313.9	223.2	112.4	67	75.3	30.7	1843.8
2002	32.2	66.3	185.7	252.8	342.9	317	247.1	329.3	237.7	82.7	25.7	34.7	2153.9
2003	45.8	88	180.2	218.7	279.1	247.2	287.3	219.1	198.8	97.4	22.3	32.4	1916.3
2004	29.2	82.8	144	264.9	241.6	246	227.7	229.5	143.2	72.7	83.4	46.1	1811
2005	41.6	53.1	189.2	262.1	204.4	257.7	280.5	204.4	207.6	155.7	50.7	42	1948.9
2006	40.2	60	150.8	187.1	254.4	344.4	354.5	234.9	197	64.2	69.5	39	1996
2007	51.4	38.2	148.3	263	223.3	296.2	236	225.3	148.1	91	56.6	25.1	1802.5
2008	38.4	94.5	136.1	205.5	307.8	311.8	322.6	148.2	112.5	110.7	60.6	35.8	1884.5
2009	51.69	63.45	95.5	280.55	288.34	262.75	220.5	260.39	214.48	103.65	18.46	20.94	1880.71
2010	37.68	37.01	164.51	200.59	247.05	326.47	302.1	172.28	162.41	129.69	53.59	30.19	1863.57
2011	52.91	94.22	213.8	250.85	285.88	327.32	231.07	211.45	171.06	144.25	53.72	35.76	2072.29
2012	39.34	97.02	179.11	183.26	312.57	207.37	247.75	204.6	146.26	86.17	47.55	24.97	1775.98
2013	46.88	61.25	256.32	236.49	285.33	263.9	293.08	271.78	192.31	113.69	62.79	33.35	2117.17
2014	14.42	23.38	164.22	255.65	220.36	207.87	336.78	231.91	243.33	51.62	5.05	51.35	1805.94
2015	20.7	66.46	158.76	230.41	214.02	247.1	212.28	340.13	166.76	160.04	46.11	56.07	1918.85
2016	50.91	108.73	118.05	185.26	301.55	293.91	313.68	209.46	205.91	87.9	43.29	61.66	1980.32
2017	46.2	93.73	148.18	208.17	307.38	279.01	279.67	239.34	99.91	89.84	55.67	19.73	1866.83
2018	36.25	60.76	165.56	231.6	425.23	319.42	389.55	252.63	187.91	121.85	45.5	17.53	2253.8

In the early 1980-ties SMHI had a network of twelve stations equipped by sun-tracking pyrheliometers. In the beginning they were measuring the sunshine duration using the limit 200 Wm^{-2} and after a few years this was changed to the by WMO recommended definition of 120 Wm^{-2}. A comparison afterwards indicated a difference of about ten percent in monthly values of sunshine duration using these two limits; slightly less difference in summer and higher in winter.

Regarding the sensitivity of old sunshine recorders a list can be found on page 15 in Ångström (1928). The Hamberg instrument was found to have an average sensitivity of 174 Wm^{-2} (0.25 gr.cal. cm^{-2} min^{-1}) within an interval of ±0.10 gr.cal. cm^{-2} min-1 (±70 Wm^{-2}). This instrument is not so far off from the modern definition of 120 Wm^{-2}. But, he also refers to an investigation by Westman of five Campbell-Stokes instruments. They vary between 209-362 Wm^{-2}.

The introduction of heating the Campbell-Stokes heliographs increased the number of hours observed. This was studied by Rodhe (1975) who found a yearly average increase of 27.6 hours of sunshine for the period Feb 1969 to Dec 1974. This correction can be added to all yearly values from 1939 to 1971 when the heating was introduced.

Before that (1939) the Hamberg modified Jordan sunshine recorder was used. And that instrument is assumed not to be affected by rime and dew in the same way. But, as was noted already by Hamberg, Westman and Ångström this and older heliographs had a slightly lower sensitivity. Therefore, it is plausible that the values should be slightly increased for these monthly values. An ad hoc value could be a correction factor of 1.04.

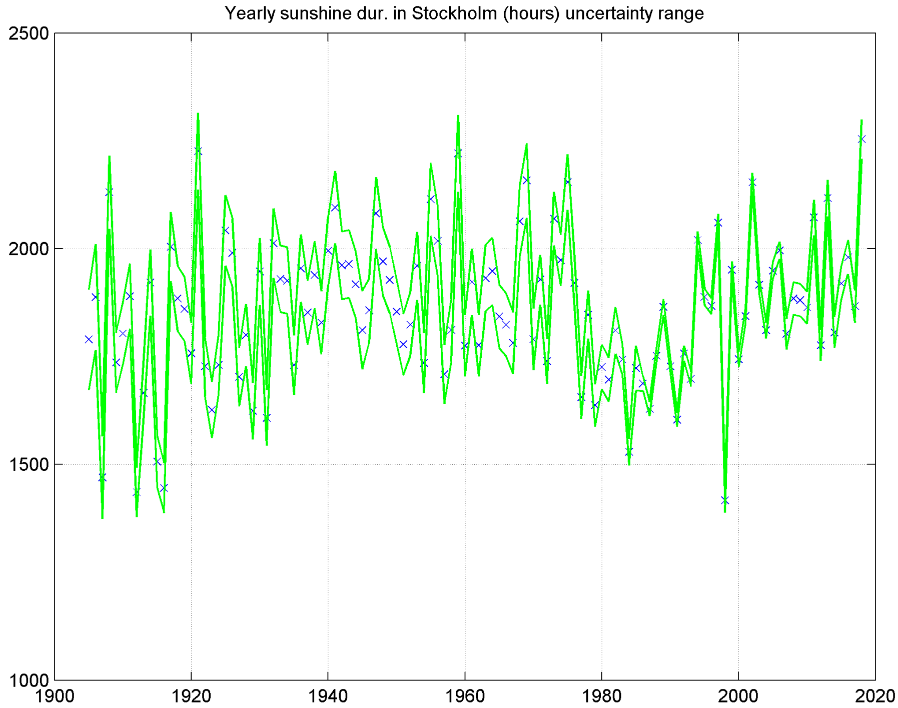

Figure A3:1 Yearly sum of sunshine duration (hours) observed at Stockholm 1905-2018 indicated by blue crosses. *Values are corrected for rime-dew effect (1905-1907, 1939-1970) and for lower sensitivity (1905-1938, 1983-1985). A rough estimate of the uncertainty (2σ) is given by the range between the green lines.*

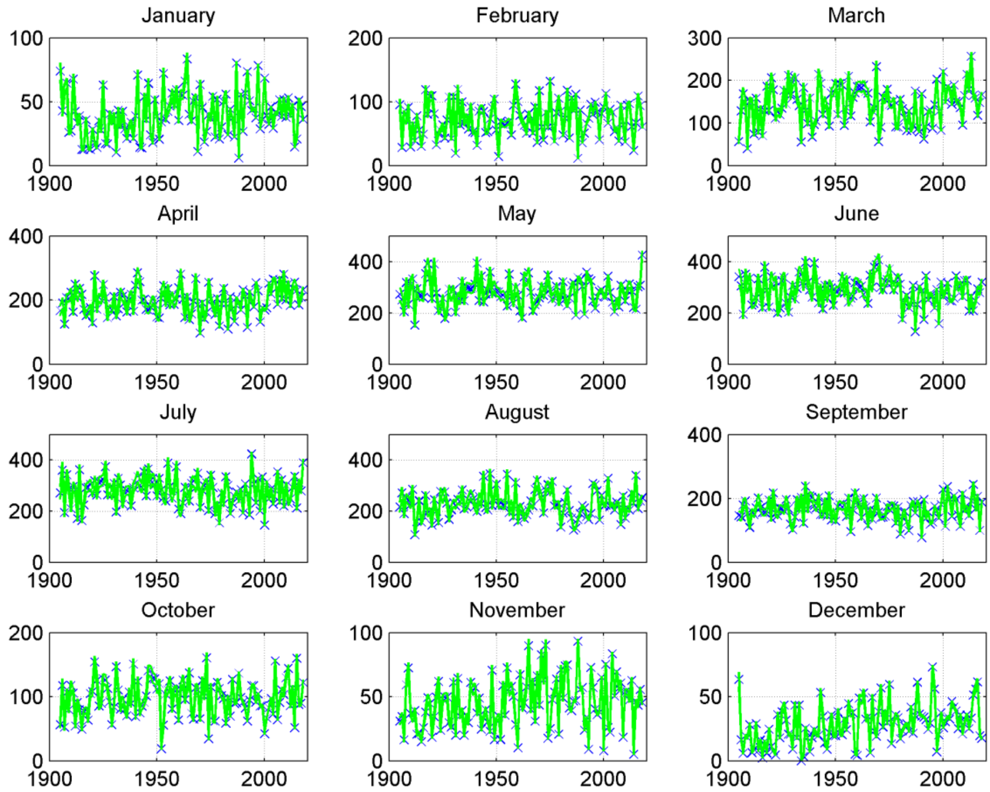

Figure A3:2 Monthly sunshine duration (hours) at Stockholm 1905-2018. Values are corrected for rime-dew effect (1905-1907, 1939-1970) *and for lower sensitivity* (1905-1938, 1983-1985*). A rough estimate of the uncertainty (2σ) is given by the range between the green lines.*

14.2 Uncertainty analysis of monthly values of sunshine duration

A rough *ad hoc* estimate of the uncertainty during different periods (related to the present monitoring position at KTH) was done. It shows that the oldest **monthly values** have a general uncertainty of ±8% (2σ) and the latest period ±4%. The uncertainty for yearly values is reduced slightly as random errors tend to level out. But, a large part of the uncertainty is probably not random and there is a large autocorrelation between months so roughly the oldest **yearly values** probably have an uncertainty of about ±5%. During the period at KTH-location when it was measured using a pyrheliometer the uncertainty of the yearly sunshine duration was probably reduced to ±2%. But, after the revision of the network in 2007 the pyrheliometer was replaced by a simpler device and thus the uncertainty grew. The magnitude may be around ±4%.

14.3 Comparison versus Helsinki

There are several long-term series of sunshine duration available in Europe. The most nearby to Stockholm is Helsinki, Finland. By personnel communication with Anders Lindfors, Finnish Meteorological Institute, raw data was compiled. No corrections have been applied but some rough filling of missing data to achieve a full data set.

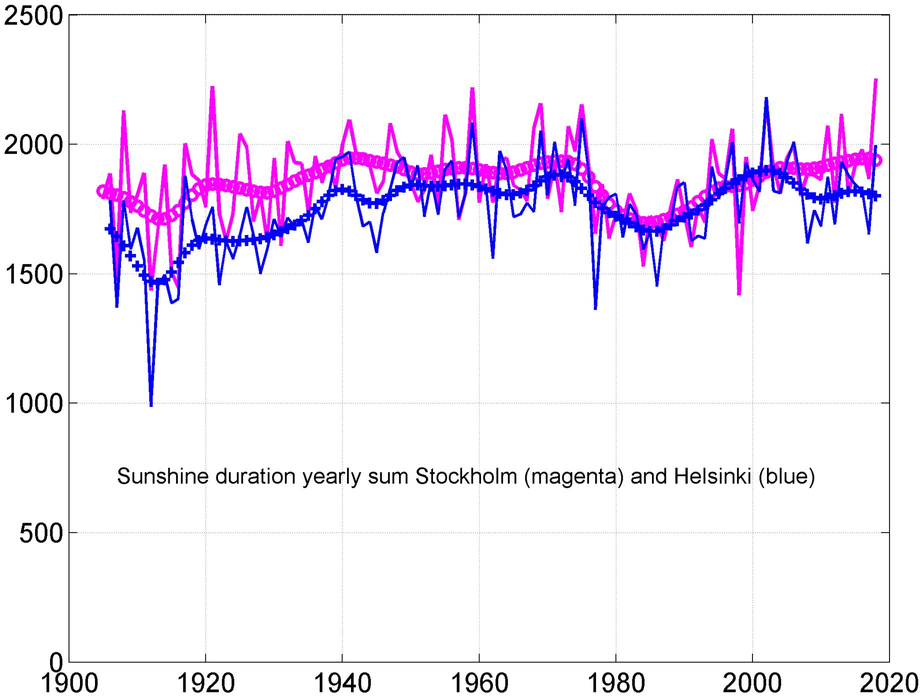

Figure A3.3 Yearly sums of sunshine duration observed in Stockholm (magenta) and Helsinki (blue). Also plotted are smoothed values.

There is an overall similarity of the two records. But, there are also a few disagreements worth noting. The first one that Stockholm-values are larger than the Helsinki ones in the first roughly 50 years may be explained as follows. The oldest part of the Stockholm-series is corrected for rime-dew effect on the instrument until the heating was introduced in the 1970-ties. There is also a correction for the instruments with lower sensitivity that was used during many years in the beginning.

The last part of the series shows a clear discrepancy. One explanation might be that from 2007 and onwards a new simpler instrument has been used at Stockholm that may be more sensitive than it should. The graph suggests this, but it has to be studied before a more certain conclusion can be stated.

Assuming that the oldest part of the Helsinki series should be slightly higher if corrected for dew-rime-problems and maybe sensitivity of old heliographs the overall impression of the two series is that they vary in the same way. And there is no secular trend. On decadal scales there are variations. For example periods with low sunshine duration has been observed 1910-1920 and in the 1980-1990-ties.

The individual year deviating most is 1912, which is the year of the Novarupta volcanic eruption.

A final comment is that these series should be more thoroughly scrutinized, corrected and studied than has been possible within this project.

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Swedish Meteorological and Hydrological Institute
SE 601 76 NORRKÖPING
Phone +46 11-495 80 00 Telefax +46 11-495 80 01

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