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Effects of pollution and ventilation

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Global Radiation Measurements in the Operational KNMI Meteorological Network

Effects of pollution and ventilation

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Samenvatting, conclusies en aanbevelingen

Van half december 1995 tot en met juli 1996 hebben er 4 pyranometers deelgenomen aan een onderzoek om te bepalen hoe groot het effect van *vervuiling* is, wat de invloed van *ventilatie* daarop is en, of het aanbrengen van een *water- en vuil-afstotende coating* betere metingen oplevert. De 4 meters worden aangeduid met

Referentie pyranometer Deze meter werd 2 maal per dag ('s ochtends vroeg en vroeg in de middag) schoongemaakt. De signalen van de overige pyranometers zijn vergeleken met die van deze referentie.

Geventileerde pyranometer Deze pyranometer had een Eigenbrodt-ventilator gemonteerd, die continu (zonder verwarming) heeft aangestaan gedurende de testperiode.

Gecoate pyranometer Op de 'dome' van deze pyranometer is de coating *Clear Shield®* aangebracht ter reductie van vervuiling.

261 Het teststation 261 bevatte al een standaard pyranometer, aangeduid met 261. Deze meter heeft ook meegedaan aan de test door hem een half jaar te laten staan en niet schoon te maken. Dit is de manier waarop de CM11-stralingsmeters operationeel in gebruik zijn.

De sensoren zijn geijkt voor de aanvang van het experiment (op 261 na, die stond nog opgesteld). Na afloop van het experiment zijn alle 4 de sensoren opnieuw geijkt (27-8-'96), waarbij het grootste verloop 0.5% was voor de gecoate pyranometer. Gedurende de maanden januari tot en met juni 1996, is alleen de referentie 2 maal daags schoongemaakt. Begin juli zijn de overige meters ook weer schoongemaakt om te kijken of de resultaten van de laatste maand weer bij elkaar zouden komen. De meetresultaten die gebruikt zijn voor de analyse, zijn 10-minuut gemiddelden, dagsommen en maandsommen.

Resultaten

Gecoate pyranometer

Direct na de ijking (eind december 1995) was de overeenkomst tussen de gecoate pyranometer en de referentie goed. In januari was de maandsom van de gecoate pyranometer 4.5% lager dan die van de referentie; in juni was dit nog 1.5%. Dit verschil van 3% is nagenoeg lineair verlopen over deze 6 maanden. De gecoate pyranometer vertoonde dus een toename in het signaal van 0.5% per maand vanaf januari tot eind juni. Vervuiling zou juist een afname in het signaal veroorzaken, de ijking bleek niet verlopen te zijn, dus waarschijnlijk is dit verloop te wijten aan 'veroudering' van de coating. Voor de maand juli, na schoonmaken van de gecoate pyranometer, was het verschil met de referentie 0.2%.

Geventileerde pyranometer

Van januari tot en met april, namen de maandsommen af van 0.4% tot 3.8% onder het niveau van de referentie, oftewel 0.85% per maand. De geleidelijk groeiende hoeveelheid vervuiling op de dome van de pyranometer was duidelijk te zien als een 'ring' rondom de onderkant van de bol, daar waar de lucht van de ventilator omhoog geblazen wordt. In juli, na schoonmaken van de dome in het begin van de maand, kwam de geventileerde meter 0.5% hoger uit dan de referentie.

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In januari was de maandsom van 261 1.4% lager dan die van de referentie. Van februari tot en met juni varieerde dit tussen 0.1% hoger en 0.2% lager dan de referentie. In juli (na schoonmaken) gaf 261 0.6% meer dan de referentie. Het blijkt dus dat de metingen van 261 het beste vergelijkbaar zijn met die van een pyranometer die 2 maal per dag schoongemaakt wordt.

Conclusies

De operationele globale stralingsmetingen zoals ze tot op de dag van vandaag gedaan worden, leveren de best mogelijke resultaten op. Verbetering kan optreden door ventilatie, maar alleen als de meters een aantal malen per week schoongemaakt worden. De coating lijkt vooralsnog niet stabiel genoeg om operationeel te gaan gebruiken. Uit de test is ook gebleken dat de instrumenten met zorg geïnstalleerd dienen te worden, daar er fouten kunnen optreden van enkele procenten, wanneer ze niet goed horizontaal geplaatst zijn. De huidige manier van ijken levert geen grote, doch wel waarneembare fouten in de metingen.

Ventileren vanwege een reductie in de maandsommen ten gevolge van ijs, rijp en/of sneeuw is niet aan te bevelen. Wanneer er 10 van zulke dagen per half jaar optreden, is de reductie in de totale halfjaarlijkse som ongeveer 0.25%. Echter, de pyranometer die een half jaar geventileerd heeft gewerk, leverde een totaal van 2.8% minder dan de referentie.

Aanbevelingen

Voor de operationele KNMI-stations waar de globale stralingsmeters niet regelmatig schoongemaakt worden, levert de huidige meetmethodiek (van de meters afblijven, niet ventileren) de beste mogelijke resultaten. Daarom dient de huidige methode gehandhaafd te blijven.

Summary, conclusions and recommendations

From half December 1995 until the end of July 1996, 4 pyranometers have been involved in an experiment to determine effects of *pollution*, the influence of *ventilation*, and if the use of a *water and dirt-repellent coating* would result in better measurements. The 4 pyranometers are denoted by

Reference pyranometer This instrument was cleaned twice per day (early in the morning and early in the afternoon). The signals from the other pyranometers were compared to those measured with this reference.

Ventilated pyranometer This pyranometer was equipped with an Eigenbrodt ventilator that has been working (without heating) throughout the whole test period.

Coated pyranometer A coating with the name *Clear Shield®* was applied to the dome of this pyranometer to reduce the amount of pollution.

261 Test station 261 already contained a standard pyranometer, denoted by 261. This meter also participated in this test by collecting its measurements without cleaning the instrument during the test period. This is the way the CM11 pyranometers are used in the KNMI operational network

The sensors were calibrated before the start of the experiment (except for 261, which was already in use). After the experiment all 4 sensors were calibrated again (27 August, 1996). The largest deviation in the calibration was found to be 0.5% for the coated CM11. During the period from January until the end of June 1996, the reference was cleaned twice per day. At the beginning of July the other 3 sensors were also cleaned, to see if the results of the 4 sensors would then become equal again during the last month. The measurements that have been analysed, are 10 minute averages, daily totals and monthly totals.

Results

Coated pyranometer

Immediately after the calibration (the end of December 1995), the agreement between the coated pyranometer and the reference, was good. In January the monthly total of the coated pyranometer was 4.5% lower than that measured by the reference; in June this had changed to 1.5% too low. This increase of 3% almost went linearly from January to June: an increased of 0.5% per month. Pollution should cause the signal to decrease, and it was found that the calibration remained stable. Therefore, it is believed that the increase is caused by 'ageing' of the coating. In July, after cleaning the dome, the difference with the reference was 0.2%.

Ventilated pyranometer

From January until April, the monthly totals decreased from 0.4% to 3.8% below the reference, or 0.85% per month. The gradually growing amount of pollution on the dome was clearly visible as a 'ring' around the bottom of the dome, where the opening for the air from the ventilator is located. In July, the cleaned ventilated pyranometer produced a monthly total of 0.5% higher than the reference.

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In January the monthly total of 261 was 1.4% lower than the reference. From February until June, this varied between 0.1% higher to 0.2% lower than the reference. In July, after cleaning 261, the monthly total was 0.6% higher than the reference. It appears that the measurements of 261 agree best with those of a pyranometer that is cleaned twice a day.

Conclusions

The operational global radiation measurements as they are performed today, yield the best possible results. Ventilation can improve the measurements, but only if the sensor is cleaned several times per week. The coating seems to be too instable to use operationally. From the test it is also concluded that the instruments must be installed with great care for operational use. If the instruments are not aligned horizontally in a proper manner, errors in the order of several percents can occur. The current method of calibration does not cause large, but still noticeable errors in the measurements.

Ventilation because of a reduction in monthly totals due to ice, ripe, and/or snow, is not recommendable. If a half year contains 10 of such days, the reduction in the half year total is approximately 0.25%. However, the pyranometer that has operated with ventilation for half a year, measured 2.8% too little compared to the reference.

Recommendations

For all operational KNMI stations where the global radiation sensors are not regularly cleaned, the currently used measurement method (don't touch the meters, don't ventilate) gives the best possible results. Therefore, this method should remain as it is.

Chapter 1

Setup of the experiment

1.1 Introduction

In the KNMI operational meteorological network are approximately 35 automatic stations where global radiation is measured with (Kipp & Zonen) CM11 sensors. The CM11 sensors have proven over a considerable period of time, to be good, reliable and stable instruments. Their calibrations tends to change only slightly over a period of a year, making them excellent instruments for unattended automatic operation.

Pyranometer measurements are essential for investigation of the Earth's radiation budget. The amounts of radiation that are of importance for this research are in the order of approximately 10 Wm^{-2}. Further, the WMO (1983) prescribes that daily totals of global radiation should have errors no larger than 5%. These figures can be used as an indication of the required accuracy of global radiation measurements. Some important factors that influence the accuracy of global radiation measurements are

Calibration The calibration factor converts the measured voltage into Wm^{-2}. For high radiation levels in the order of 1000 Wm^{-2}, an accuracy of 1% is minimally required (10 Wm^{-2}). Therefore, the accuracy of the calibration should also be 1% or better.

Instrument characteristics If the calibrations are performed in a laboratory, usually a parallel beam of light is used as a calibration source. This method can yield reproducible calibration factors, but errors due to, e.g., offset, erroneous cosine responses, azimuthal dependence, temperature dependence, non-linearity of the detector, solar elevation dependent calibration factors, signal delay, etc, are not taken into account. Instrument characteristics should also be determined for accurate global radiation measurements.

Measurement site The sites for global radiation measurements should be chosen with care. If the horizon is (partly) obscured or if other obstacles are covering part of the sky, the daily totals can contain considerable errors.

Maintenance The instruments should be checked regularly. If, for example, an instrument is newly installed for unattended operational use, and for some reason soon thereafter pollution is present on the dome (birds!), the accuracy of the measurements will be poor.

Installation procedures It is essential that the instruments are aligned properly when they are installed for their measuring period in the network. The combined effect of cosine error and improper alignment, can cause errors of several percents.

An excellent overview of how all these factors influence the measurements, is described in the report *Improved Measurements of Solar Irradiance by Means of Detailed Pyranometer Characterization* (see bibliography). It contains theoretical evaluations of various instrument features, as well as results from various outdoor and laboratory tests, that won't be discussed in this report.

The calibrations of CM11's at KNMI (the calibrations are performed in the KNMI-calibration laboratory, see sect. 1.2.1) are accurate and reproducible within about 1%. To see how large different pyranometer measurements are when they are measuring under identical situations, an experiment was set up with 4 CM11's. This took place at the KNMI test site, which is located at the south side of the KNMI main building in, De Bilt, The Netherlands (52.1° N, 5.18° E). The test started in December 1995, and continued until August 1996.

One of the pyranometers was equipped with a ventilator. The dome of the second pyranometer was treated with a water and pollution repellent coating. The third pyranometer was measuring in a way identical to the pyranometers in the KNMI operational network. The fourth and last pyranometer was carefully cleaned twice every day, and the other three instruments were compared to this 'reference'.

In this chapter the setup of the experiment is described. Section 1.2.1 discusses the calibration of CM11's by the KNMI calibration laboratory. In section 1.2.2 the method of measuring and the data acquisition is described. The last section of this chapter (1.2.3) gives a description of the test site.

1.2 Instruments

For the experiment 4 'old' pyranometers were used, i.e. they have all been used in the KNMI operational network before. The 4 pyranometers are identified by their unique KNMI-number, which are given in Table 1. All pyranometers are identical CM11's, manufactured by Kipp & Zonen (Delft, The Netherlands).
One of the four pyranometers was equipped with an Eigenbrodt ventilator (instrument nr. 01.23.010.27). This ventilator was mounted on the side of the CM11. It blows air from the bottom of the glass dome upwards. Although a heater was present, the ventilator was only used without heating. The ventilator has been working all the time during the experiment.

The pyranometer called 'coated', (instrument nr. 01.23.010.05) had been treated with the coating *Clear Shield®* (RITEC International Ltd.). This coating is usually applied on locations (glass) which are difficult to clean and which pollute easily. It keeps glass surfaces clean, and it is water repellent. If this coating would work on pyranometer domes, the advantage for operational unattended setups is evident.

There was already one pyranometer in use in the KNMI-test field. It has also been used in this experiment. The test-station at KNMI in De Bilt, is identified as KNMI-station 261. Therefore, this pyranometer is referred to as '261'. During the whole test-period this instrument has not been touched or cleaned. In the operational KNMI network, all instruments operate unattended for a period of a half year to a year. The intention of having 261 in the experiment was to find out how our current operational setup performs compared to the other systems.

The last pyranometer was the 'reference', an ordinary CM11, which was cleaned every morning and early in the afternoon (except during the weekends). The measurements of this pyranometer were considered as the 'correct ones'. The other pyranometers were compared with this reference.

1.2.1 Calibration

Because the instruments in the experiment are 'old' instruments, they all had a calibration history. At KNMI CM11's are calibrated once per year. The instruments have proven over the years that they do not drift over such a period of time.

The method of calibration is based on comparison with a CM11-calibration standard under a 500W halogen lamp. The CM11-standard and the instrument to be calibrated, are mounted on a rotating arm. First the standard is positioned under the lamp and its output signal is measured. Then, the other pyranometer is placed under the lamp, in the same position where previously the standard was. The signal from the pyranometer 'to be calibrated' is then measured. This procedure is followed several times. The calibration factor of the standard is known, and that of the second pyranometer can be determined this way.

All pyranometers in the KNMI network are calibrated this way with an accuracy of 1%, and they have calibration factors of 4.00 μV/(Wm^{-2}). If during a calibration an instrument is found to have a deviation in the calibration factor larger than 0.04 μV/(Wm^{-2}), the calibration factor will be adjusted. However, this hardly ever occurs.
In Table 1 the first calibration factors are given for all instruments. This first calibration roughly corresponds to the date of purchase of the instruments and is an indication for their 'age'. The calibration factors before and after the test period are also shown.

1.2.2 Data acquisition

The data acquisition for the experiment was arranged in the same way the data is acquired in the KNMI operational stations. All sensors are connected to a so-called SIAM (System Intelligent Adaption Module). This is a 'computer' that reads the voltage of the sensor every 12 seconds, multiplies it with the calibration factor, performs some statistical calculations, and produces a digital output string. This output string contains the last 12 second measurement, 1 and 10 minute running averages with the minimum and maximum values measured in these time intervals, and information on the status of the instrument. The output string is read by a data-acquisition computer, the AWS (Automatic Observing System). The measurements are stored in the AWS, until they are copied from the test site to a desktop computer for processing the data (by a modem connection). Because of the precision of the SIAM, the smallest step between 2 measured irradiances is 1 Wm^{-2}.

1.2.3 Test site

The test site was located at the south of the KNMI main building in De Bilt (52.1° N, 5.18° E). It is a field of approximately 250 (east-west) by 400 (north-south) meter, surrounded by trees from the south-east to the south, west and north-west. The instruments were located approximately 100 m from the north side of the field, in the middle of the east-west direction. The trees with high tops obscure the horizon up to 10° for a few locations, but for the largest part only 7 to 8° is obscured.

The KNMI-building is located in De Bilt, which is approximately 5 km to the east of Utrecht. To the north at ~500 meter distance starts the town of Bilthoven with some apartment buildings. To the east, south and west, the first building are all a few km away. There is some woodland and some meadow in the direct vicinity of the KNMI-building.

Three of the instruments were installed at the ends of an arm of an 'H'-shaped aluminium construction, 1.5 m above the grass, approximately 1 meter from each other. The fourth pyranometer (261) was already in place before the experiment started and was not moved. All instruments were within 4 meter of each other to avoid spatial differences in the measurements.

Table 1 The 4 pyranometers used in the experiment with their unique KNMI identification number. First calibration dates and calibration factors are shown, and also the calibration factors before and after the experiment. The calibration factors are in units of μV/(Wm^{-2}).

ID number	First calibration	Calibration factor			instrument
		first	before experiment	after experiment	
01.23.010.05	26/06/95	5.00[a]	4.01	3.99	coated
01.23.010.15	10/30/89	3.99	3.99	4.00	reference
01.23.010.27	09/18/89	4.00	4.02	4.01	ventilated
01.23.010.48	09/16/89	4.01	4.01	4.00	261

a. All KNMI-pyranometers have approximately the same calibration factors. Before the start of the experiment, the calibration factor was changed from 5 to 4 μV/(Wm^{-2}).

Usually CM11's are aligned in a similar manner to avoid differences in the measurements due to differences in orientation of the themopiles. The reference, the coated pyranometer and 261 were all aligned so that the spirit levels pointed to the south-east. The spirit level of the ventilated CM11, is mounted differently and could therefore not be used. The ventilated pyranometer was oriented with the signal cable coming out of the instument pointing to east.

Chapter 2

Results

2.1 Monthly totals

The monthly totals are useful to see how the instruments behave, leaving out detailed information about the individual measurements. In Fig. 2.1(b), the monthly totals of the global radiation are shown. From this figure it can be seen that the absolute differences are small. It is, however, more interesting to look at the relative difference, which are shown in Fig. 2.1(a). They are discussed below.

Coated pyranometer In January, the coated pyranometer is 4.5% lower than the reference, in June it was only 1.5% lower. A part of the difference with the reference in January was caused by special conditions during this month. There were several days in January on which ice was present on (some of) the domes of the pyrano-

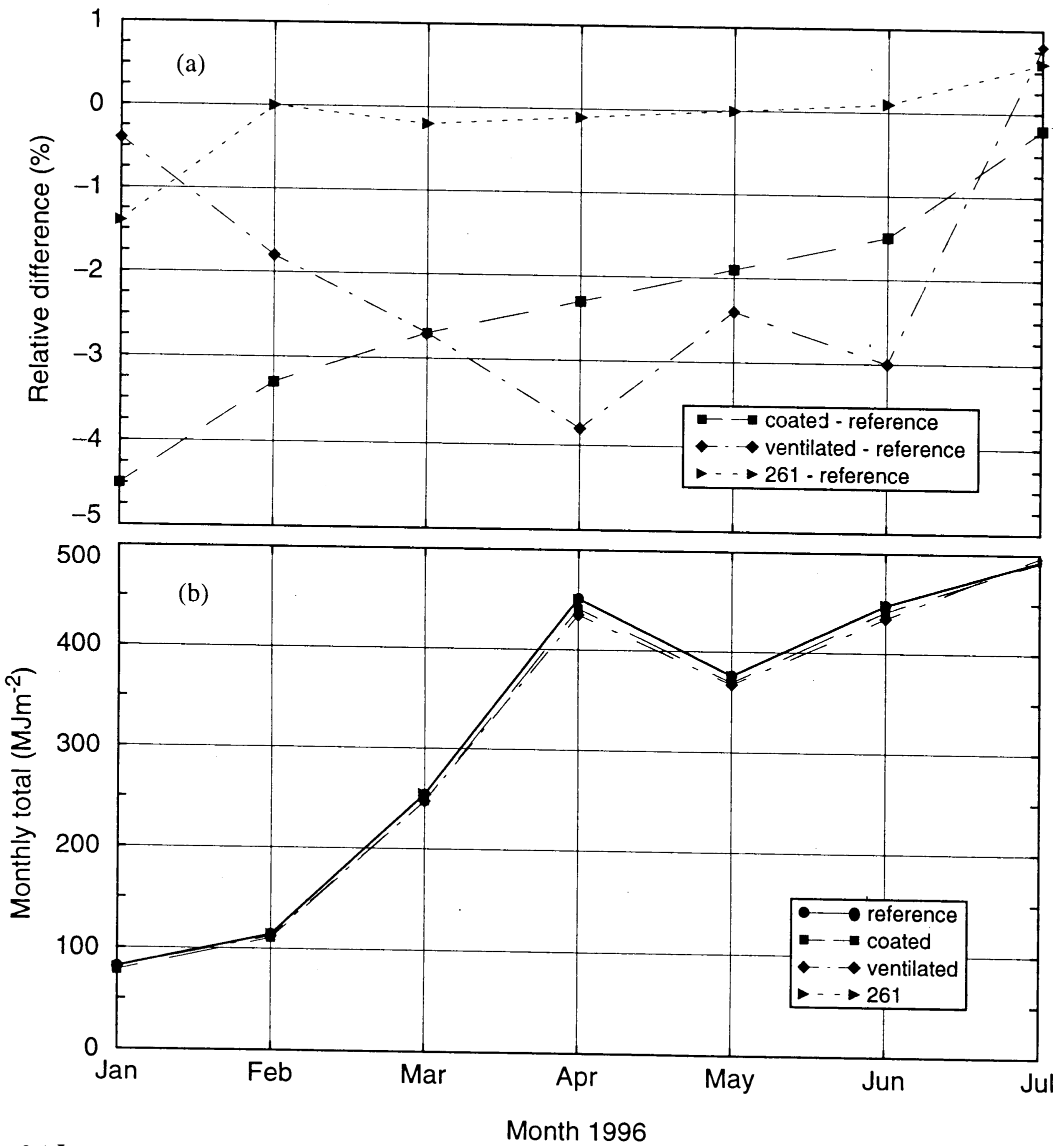

Figure 2.1 In (b) the monthly totals of the global radiation of the 4 pyranometers are shown. The curves of the reference and 261 are so close to each other so that they cannot be distinguished. In (a) the relative differences compared with the reference, are depicted. A negative difference means that the indicated pyranometer produces a signal lower than the reference.

meters. It could not always be simply wiped of with a piece of cloth because it was really stuck, depending on the origin of the ice: frozen rain/snow or ripe. Sometimes (some of the) ice could be removed from the reference, the dome of the coated pyranometer was more often covered with (more) ice than the reference, and the ventilated pyranometer had the least ice problems. When the sun rises, the ice melted on the side of the dome that was directly illuminated by the sun. Then the beam of sun light entered the dome and was reflected downward onto the detector by the ice on the 'cold' side of the dome. This temporarily caused the readings of the reference to be too high, but integrated over the whole day, the presence of ice decreased the daily total (see also sect. 2.3.1).

The almost linear increase of the curve for the coated pyranometer that is observed between January and June, suggests a gradual change in the response of the instrument in time. This could be caused by a change in the calibration factor. However, from Table 1 (sect. 1.2.1), it can be seen that the calibration factor before and after the experiment, differed only 0.5%. This cannot explain gradually changing difference between the coated pyranometer and the reference of 3% over a period of six months.

The spectral transmission of the coating was not measured at the start of the experiment. Neither was there any information on the temporal change in the spectral transmission of the coating due to exposure to sunlight. If such a change has occurred in the visible region of the spectrum, it might be an explanation for the decreasing difference between the coated pyranometer and the reference [the 500W calibration lamp peaks in the infrared, so that the calibration factor hardly needs to be affected]. However, to draw definite conclusions on the spectral features of the coating, it should have been measured before starting the experiment, and after the test it should have been repeated. There are, at the moment, no intentions of doing this, considering the results of the other pyranometers.

Another possible explanation may be the alignment of the pyranometers. At the beginning of the experiment, all pyranometers have been put in the best horizontal position as possible, using the standard spirit levels. Pyranometers are known to have imperfect cosine responses, and additionally, they may also exhibit some form of azimuthal dependence. If an error due to the cosine response is present, it is largest during the winter months because of low solar elevations, decrease during spring and summer, and increase again in autumn. However, the experiment was stopped in August and there will be no further measurements. Therefore, it is at this time not possible to make any definite statements about what caused the behaviour of the coated pyranometer.

In the beginning of July the coated pyranometer was cleaned again, and the difference compared to the reference for that month is –0.2%.

Ventilated pyranometer The ventilated pyranometer was installed in December 1995 with a clean dome. In January the monthly total of this pyranometer was 0.4% lower than that of the reference. It was observed during the daily control of the instruments, that gradually a ring of pollution developed around the bottom of the dome. This pollution was thick at the bottom of the dome, and gradually became thinner towards the top. Due to this pollution, the difference with the reference increased up to almost –4% in April.

The first 4 months of 1996 were relatively dry with only little precipitation. This resulted in an almost linear decrease for the curve of the ventilated pyranometer. During the months May and June, there was more precipitation, washing of some of the pollution of the ventilated pyranometer. This accounts for the varying difference of –2.5% in May and –3% in June. In July this instrument was cleaned again, as a result of which the monthly total was approximately 0.5% higher than that of the reference.

261 The monthly total of 261 in January is about 1.4% lower than the reference: there was more often ice on 261 than on the reference because of the cleaning of the reference. This reduced the monthly total for 261 with respect to the reference. However, from February to June, the reference and 261 were always within 0.5% of each other. In July, after cleaning 261, it was about 0.6% higher than the reference. It is possible that the small increase of 261 compared to the reference during the period March-June, is also caused by differences in cosine response.

Conclusions

Looking at the monthly totals of global radiation measurements, ventilation should not be used if the instruments are not regularly cleaned. In a period of a few months, the monthly totals can be too low due to pollution up to 4%. During the winter the totals from the ventilated pyranometer are probably better than those of the unventilated instruments. However, the contribution of the winter months to the total of a whole year, is small, whereas the reduction during the summer months due to pollution is of much more influence.

The coated pyranometer is the only one showing the gradually changing behaviour. At the moment, it is assumed that it is the ageing of the coating that causes this effect, possibly in combination with an erroneous alignment. Ageing is a long term process, it still was not finished after a period of 7 months. Therefore, it is not recommendable at this time to apply the coating to operational pyranometers. Further investigations are needed to decide what has caused this behaviour.

The results that agree best with the reference, are those measured with 261: the pyranometer that has been measuring unattended for 7 months. From operational point of view, this method is the best that is available at the moment.

2.2 Daily totals

In Fig 2.2 the deviations in the daily totals of 261, the coated, and the ventilated pyranometer compared to the reference, are shown. If the difference is negative, the corresponding pyranometer produces readings lower than those of the reference.

From Fig 2.2(a) it can be seen that relative differences in January and February show a lot of scatter, whereas the absolute differences (Fig 2.2(b)) are small. From March until the end of July, the relative differences show only little scatter, whereas the opposite occurs for the absolute difference. The relative difference is computed by subracting the signal from the reference from that of one of the other instruments, dividing the result by the signal of the reference, and multiplying it with 100%. In the winter 2 small numbers with relatively large uncertainties, are subtracted and divided by a small signal from the reference. In spring and summer, 2 large numbers are subtracted and divided by a relatively large signal from the reference. The larger uncertainties in the subtraction of small signals causes the larger amount of scatter in the winter months.

261 It is obvious from Fig 2.2(a) that 261 shows only little difference with the reference for the period March-June. In July there is a 'discontinuity' in the curve of 261 where the daily totals increase by approximately 0.5% because the dome was cleaned. *Thus the cumulative effect of pollution in the daily totals over a period of 6 months of the KNMI network pyranometers, is in the order of 0.5%.* A linear regression for the first 6 months resulted in a monthly change of approximately 0.24%, and the intercept at day 1 was −1.06%. Thus, in January the difference started at −1.06%, and at the end of June it had increased up to 0.4%.

Ventilated After cleaning the ventilated pyranometer in the beginning of July, it suddenly produced daily totals of 0.5 to 1% higher than those measured by the reference, whereas they were approximately 3% lower than the reference in June. The difference between the ventilated pyranometer and the reference had more or less stabilized since May. A linear regression showed a monthly change in the difference of −0.57%, starting at −0.5% in January.

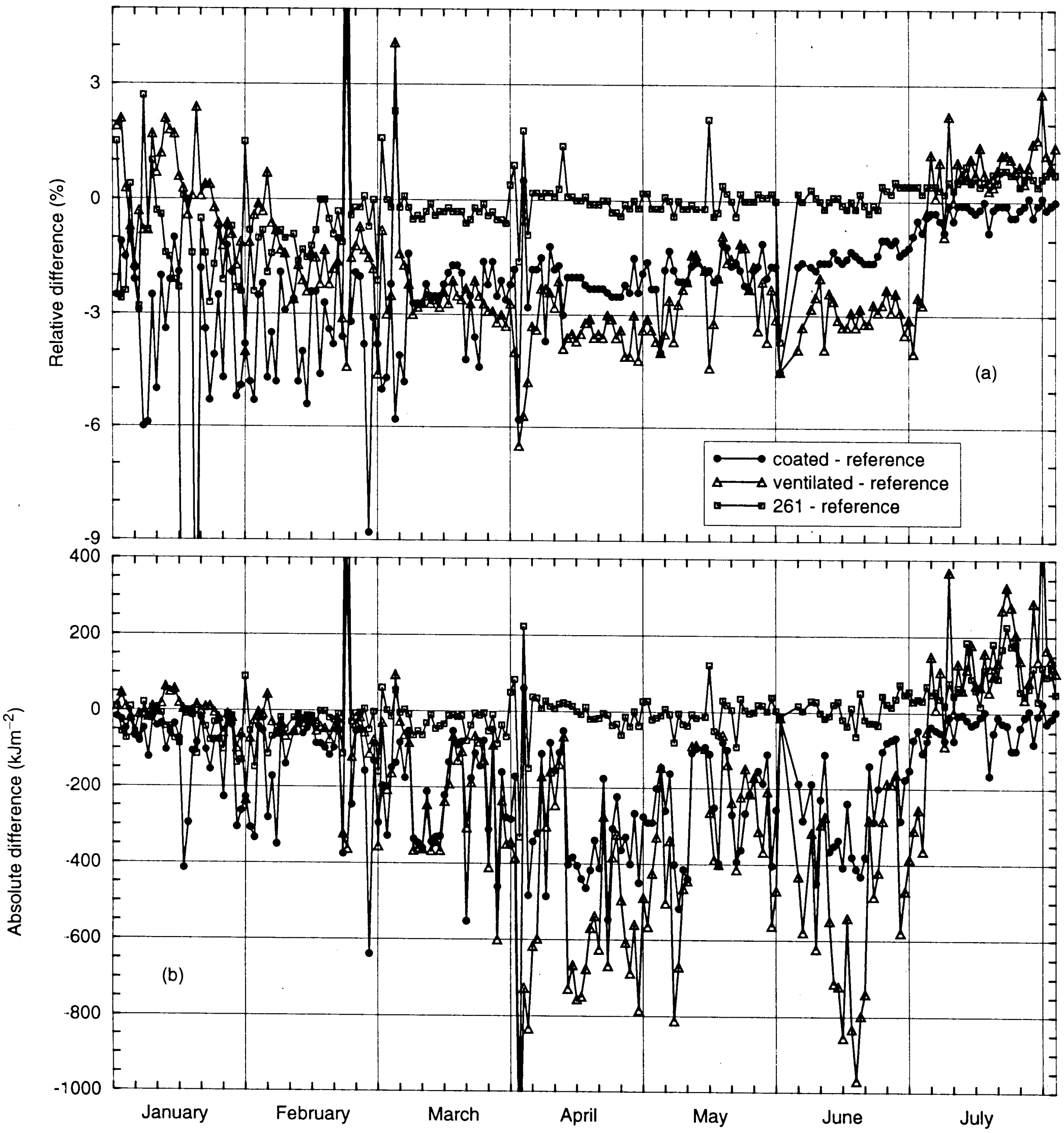

Figure 2.2 In (b) the absolute differences (in KJm^{-2}) of the pyranometers compared to the reference are shown. In (a) the corresponding relative differences are presented. A negative difference means that the indicated pyranometer produces a signal lower than the reference.

Coated The differences between the daily totals derived from the coated pyranometer and the reference, increase almost linearly from March until June. A linear regression showed that the difference starts at approximately –4.6% in January, and at the end of June it has changed to approximately –0.8%. On average, this is an increase of 0.6% per month. This drift occurred only for the coated pyranometer. Since the only difference between this instrument and the other 3 pyranometers is the application of the coating on the dome, it is believed that ageing of the coating caused this effect.

Most materials change under the influence of radiation. It is possible that the spectral transmission characteristics of the coating gradually changed during its continuous exposure to solar radiation (and in particular to the UV part of the solar spectrum).

Conclusions

Over a period of a half year, the coated pyranometer compared to the reference changed with 0.021% per day, the ventilated pyranometer with –0.57% per month, and 261 with 0.24% per month. The variation in the relative differences are large in January and February, and become smaller when the absolute amounts of measured radiation increase from March onwards to the summer. Cleaning the domes after a period of 6 months, brings all the measurements within 1% of the reference (and each other).

2.3 10 minute averages

The graphs of the daily ten-minute averages are informative in several ways. They clearly show the differences between the individual measurements due to instrumental features such as cosine response and calibration factors. If such errors are present, only their cumulative effects are observed in the monthly and daily totals. The 10 minute averages directly show such instrumental differences. The comparison of the 10 minute averages provides some insight in the accuracy of the KNMI-network of global radiation measurements in the Netherlands. Furthermore, the instruments react differently to various weather conditions. The combined effect of instrumental characteristics and the dependence on meteorological circumstances, is mostly difficult to distinguish. However, under certain specific conditions this is possible. In this section, 10 minute averaged measurements are discussed which illustrate the differences that occur between the instruments, and when possible, they are explained.

2.3.1 Snow/ice

In December 1995 and January/February 1996, several days occurred on which it snowed, and on which ice was present on the domes, either due to freezing rain or ripe. Although officially the experiment started in January 1996, the instruments were installed in December 1995. Around Christmas, there was a period of cold weather with temperatures well below 0 °C, and it snowed on a few days.

Snow, December 25, 1995

December 25, the temperature was around –3.5 °C before sunrise. During the day it went up to –0.1 °C at sunset. There was some (light) snow from 8:30 until 10:30, and the relative humidity was 100% until 16:00, when it decreased down to 82% at 19:00, to increase again to approximately 90% (all times GMT). In Fig 2.3 the global radiation measured by the 4 instruments is shown.

It can be seen from Fig. 2.3 that the measurements of the ventilated pyranometer are approximately 50 to 70% higher than those of the 3 other instruments. Because December 25 is a holiday, the reference was not cleaned this day. Therefore, also the reference produced a too low signal on this day.

The daily total of the ventilated pyranometer for this day was 1.431 MJm^{-2}, while the 3 other instruments all measured around 0.95 MJm^{-2}: a difference of 50%. It can be concluded that for the described weather conditions, the ventilated pyranometer yields the best measurements.

The instruments for the test were first installed on December 22, the day on which also the measurements started. Until December 24 it was the same type of weather: no precipitation and temperatures just above 0 °C. After December 25 until the end of the year, there were days with snow, and with rain in combination with temperatures below 0 °C, which caused all measurements to be incorrect. The total for the period December 22/31 for the reference was 25.4 MJm^{-2}, that for the ventilated pyranometer 23.8 MJm^{-2}. The total of the ventilated pyranometer thus is 6.3% *lower* than the reference. Weather circumstances as describe above, make global radiation measurements unreliable.

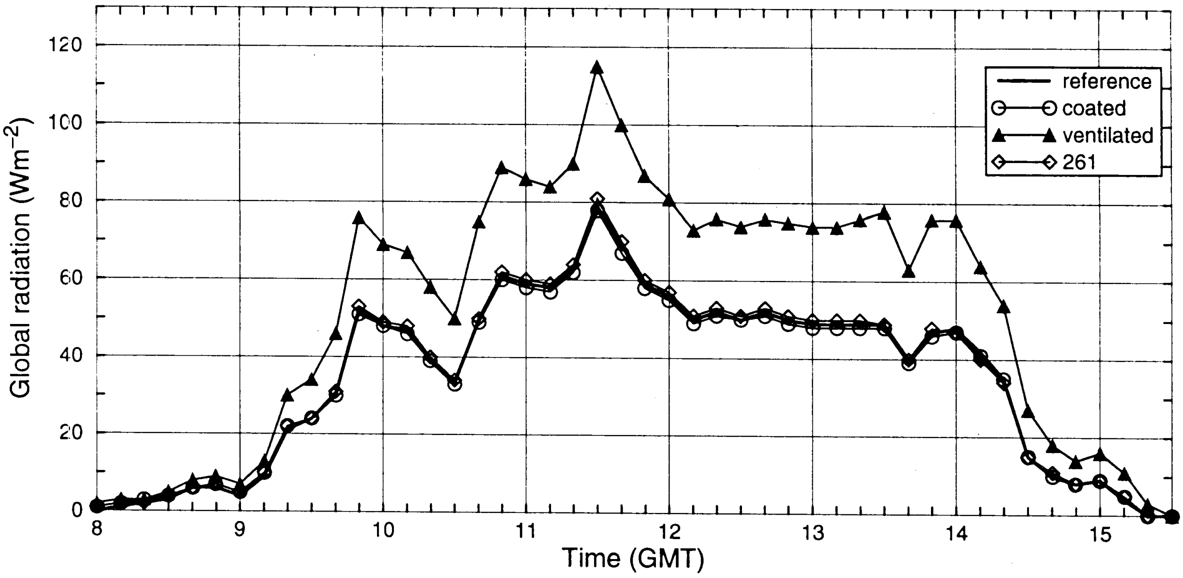

Figure 2.3 On December 25, 1995, snow covered all pyranometers, except the ventilated instrument. The reduction in the measured amount of radiation is clearly visible.

Ice, January 19, 1996

On January 19, the temperature remained below 0 °C during the whole day (highest temperature: –1.3 °C). The relative humidity was 100% during largest part of the day to decrease down to 94% in the evening. As a result of these conditions, there were thin films of ice on both 261 and the coated pyranometer. The reference was cleaned, and the ventilated pyranometer was also free of ice. The measurements are shown in Fig. 2.4.

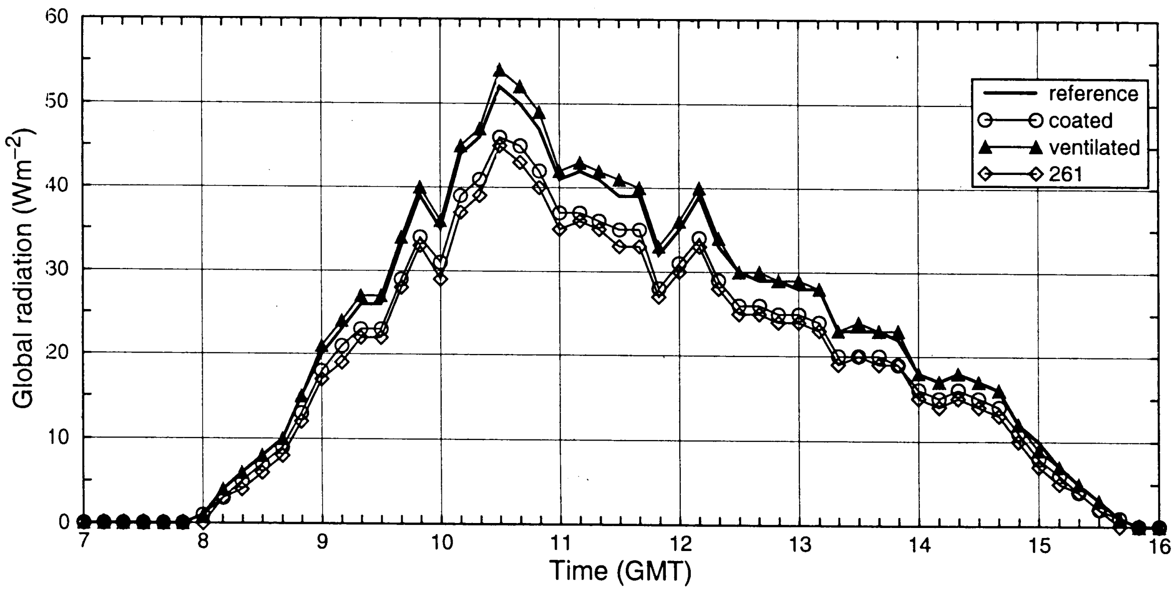

Figure 2.4 Measurements of January 19, 1996, with ice films on the domes of 261 and the coated pyranometer. The reference and the ventilated pyranometers did not have ice problems.

It can be seen from this figure that the reference and the ventilated pyranometer show good agreement. The coated pyranometer and 261 also show good agreement, but they both measure too little: they were during the whole day 12 and 16% lower than the reference. This was caused by the ice film on the domes.

2.3.2 Cloudless conditions

Measurements under cloudless conditions provide information on the correct alignment of the instruments: instrumental cosine errors and misalignment together cause the measurements to differ. In Fig. 2.5(a) the measurements of the global radiation of August 5, 1996, are shown (although it is not a day in the test period, the instruments were still operational, and it was the best day to show the features described here).

The curves representing the measurements of the 4 instruments in Fig. 2.5(a), seem to agree well. In Fig. 2.5(b), the absolute differences of the 3 instruments compared to the reference, are shown. It can be seen that the measurements of the coated pyranometer are constantly a few Wm^{-2} lower than the reference, which may be due to an offset in either the reference or the coated pyranometer. The ventilated pyranometer produces measurements that are up to 10 Wm^{-2} higher than the reference in the morning, but in the afternoon they become approximately 6 to 7 Wm^{-2} lower than the reference. If the ventilated pyranometer is not aligned horizontally properly, there will be a cosine error in the measurements. Moreover, if the measurements are compared to those obtained with another instrument that may also not be aligned properly (e.g. the reference), an extra cosine error is introduced.

It goes without saying, that much attention was paid to the individual alignment of the instruments at the beginning of the experiment, using the built in spirit levels. However, this is only an assurance that the spirit level is aligned properly, but it is not a guarantee that the detector is also aligned in the right manner. Probably the effect that is visible in the figure, is the combined effect of misalignment of the instrument due to imperfect spirit levels, and cosine errors of the instruments themselves.

Pyranometer 261 shows another deviation from the reference: the absolute difference starts small, increases when the measured signals become large, and decreases again at the end of the afternoon. This suggests an error that is proportional to the measured signal. This can be caused by an error in the calibration factor. In Fig. 2.5(c) the corresponding relative differences are shown, from which the cosine error of the ventilated pyranometer is clearly visible.

2.3.3 Clouds

Two types of cloudy conditions can be distinguished: partly cloudy and overcast. As an example of a partly clouded day, June 10, 1996 is chosen. The measurements are depicted in Fig. 2.6.

Until 5:00 GMT the relative humidity was 100%, and the reference was cleaned at 4:50 GMT. The temperature was about 11 °C during the night, and it increased to 26 °C around solar noon. It can be seen from the figure, that in the morning, when the relative humidity is 100% and there are water droplets present on the domes, there are large differences between the instruments. After 12:00 GMT, clouds developed. This caused a larger variation in the differences than before 12:00 GMT. Between 9:00 and 12:00 GMT, the differences between the coated pyranometer and the reference, and 261 and the reference (c) are almost identical. It can, however, be seen from the figure that after 12:00 GMT, a systematic difference is found between 261 and the coated pyranometer. This effect was frequently observed under similar weather conditions.

Apparently, cloud cover induces differences between the instruments in the order of 2%. The reason for this phenomenon is not yet clear. Under clear sky conditions, the global radiation consists of diffuse radiation and the direct component. When the direct component is obscured by clouds, only diffuse radiation is measured and this component is not very sensitive for cosine errors. Therefore, it can be assumed that the measurements under cloudy conditions in the afternoon, represent the 'true' irradiance, and in the morning, when the direct component with the cosine error is present, there will be a larger error. In general, on completely overcast days (with radiation levels up to 300 Wm^{-2}), the same phenomenon is observed: the ventilated pyranometer produces readings that are

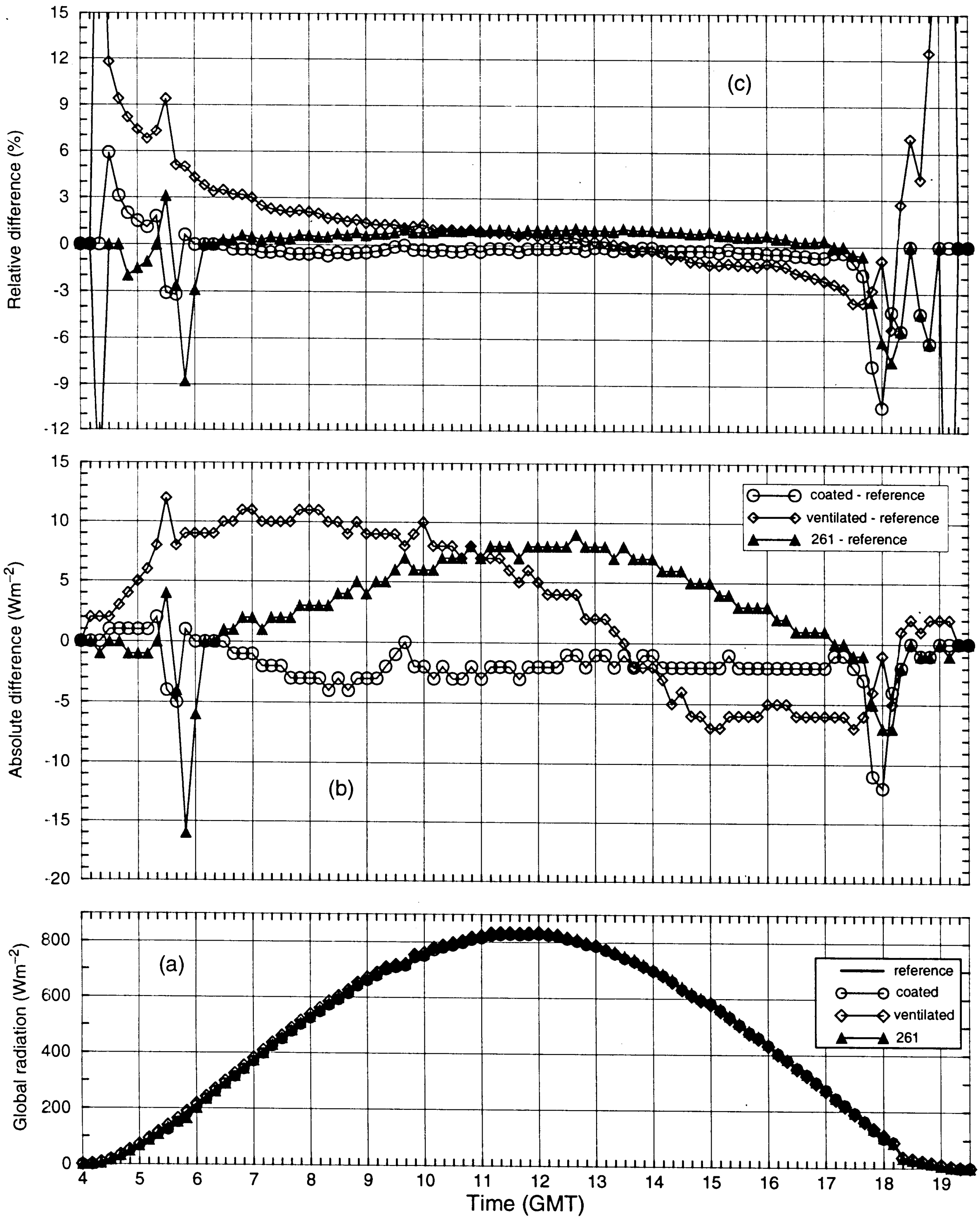

Figure 2.5 In (a) the measurements of August 5, 1996, of the 4 sensors show little difference. In (b) and (c), the absolute and relative differences compared to the reference are shown. The differences for the ventilated pyranometer are typically due to cosine errors (maybe due to misalignment of the instruments), and those for 261 for an error in the calibration factor. The coated pyranometer shows a deviation from the reference typical for an offset in one of the 2 instruments.

a little lower than those measured with the coated instrument.

2.4 Summary of the conclusions

- Ventilation of pyranometers without regular cleaning, in general causes too low readings, except when snow

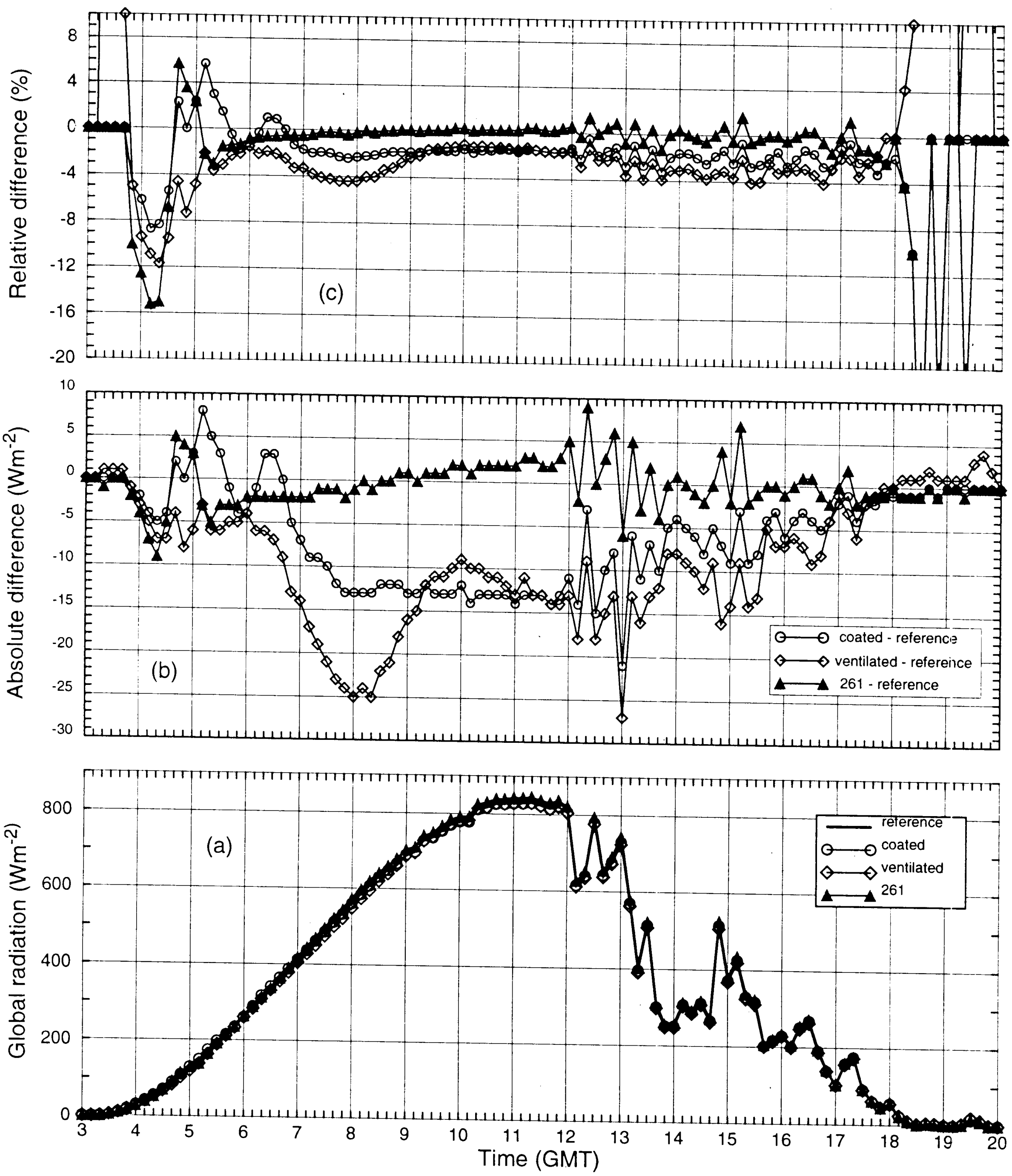

Figure 2.6 The measurements of June 10, 1996 (a), of the 4 sensors. In (b) and (c), the absolute and relative differences compared to the reference are shown. Until 12:00 GMT, the sky was cloudless, thereafter cloud cover varied between 1/8th and 7/8th.

or ice is present on the domes. Monthly totals can be 4% too low, the total sum over the period January-June 1996, of the ventilated pyranometer, was 3.3% lower than the reference.

- Applying 'Clear Shield®' on the domes of pyranometers, is not recommended. From the experiment it is concluded that transmission of the coating may have changed by 4% over a period a 6 months and still is changing.
- The current method of doing global radiation measurements in the KNMI-network, i.e. no cleaning and no ventilation, gives agreement with a regularly cleaned instrument that is better than 1% over a period of 6 months.

- Installation of pyranometers in the network must be performed with great care. Errors in the measurements due to incorrect levelling of the instruments can be in the order of a several percents!
- The current calibration procedure is thought to be only a small source of errors. However, better calibration facilities for radiation measurements are available nowadays at KNMI, and it is recommended to investigate if they can be applied to CM11 calibrations in an efficient manner.

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