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SECOND WORKSHOP ON IMPLEMENTATION OF THE

BASELINE SURFACE RADIATION NETWORK

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The World Climate Programme launched by the World Meteorological Organization (WMO) includes four components:

The World Climate Data and Monitoring Programme
The World Climate Applications and Services Programme
The World Climate Impact Assessment and Response Strategies Programme
The World Climate Research Programme

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1. OBJECTIVES OF WORKSHOP

1.1 The second workshop on the implementation of the WCRP Baseline Surface Radiation Network (BSRN) was opened by Dr. C. Fröhlich at 0900 hours on 6 August 1991 at the World Radiation Center, Physikalisch - Meteorologisches Observatorium, Davos (WRC/PMOD). Participants in the workshop are listed in Appendix A to this report.

1.2 Dr. Fröhlich welcomed participants and hoped that, as well as discussions at the workshop, there would also be time to enjoy the magnificent mountain scenery offered by Davos. On behalf of participants, Dr. J. DeLuisi (BSRN Project Manager), expressed gratitude to Dr. Fröhlich for hosting this workshop on the implementation of the BSRN and to his staff for the excellent arrangements made.

1.3 Dr. J. DeLuisi reminded the workshop of the need to strengthen the commitment to uniform global observations of surface radiation components and to assure the highest possible quality for the data gathered in order to support climate studies in an effective manner. Workshops of this type provided an avenue for interaction and co-operation between radiation laboratories and BSRN participants. It was also necessary to consider how to obtain the resources to support the BSRN and, in particular, finance for the development of radiation instrumentation that was now so pressingly required.

1.4 More specifically, the present workshop had, as agreed at the earlier meeting on the implementation of the BSRN (Washington, December 1990), been convened to review progress in studies of instrumental uncertainties, proposals for calibration and instrument traceability procedures, the contents of a draft operations manual and data management plan.

1.5 In an initial general review, it was noted that, in addition to planned BSRN measurements and other existing observations (e.g. from solar radiation networks), measurements may also be made by other groups not closely linked to the radiation climatological community (e.g. measurements by the Solar Energy Research Institute, now the National Renewable Energy Laboratory). It was recommended that strong efforts be made (e.g. through the International GEWEX Project Office and WCRP Radiation Projects Office) to make as widely known as possible the standards, methods of calibration and accuracy targets of the BSRN, and to encourage co-operation and exchange of views with these groups. In particular, in field experiments such as FIRE Phase II and, later, in the GEWEX Continental-scale International Project (GCIP), the importance of aiming for BSRN standards and instrument recommendations (see section 3) should be emphasized in order to achieve as much compatibility and comparability as possible.

1.6 Another item of particular importance was the question of the absolute accuracy of existing techniques for determining surface longwave irradiances, as being used for ground truth for the Surface Radiation Budget Climatology Project. This information was now urgently needed to be able to validate methodologies for obtaining estimates of the global distribution of the surface longwave flux from satellite data (see also paragraph 6.3).

2. REPORTS ON INSTRUMENTATION AND MEASUREMENT UNCERTAINTY STUDIES

Variability in a population of twelve normal incidence pyrheliometers (J. DeLuisi)

2.1 Changes in measurements with time from twelve normal incidence pyrheliometers (mounted on separate trackers) after initial calibration with an absolute radiometer were examined. Individual instrument values were compared with the average from all twelve instruments for each minute of operation during cloud-free viewing conditions for periods of several days. Typical results for a one-day sample for solar zenith angles varying from 30° to 85° showed that departures from the mean for the normal incidence pyrheliometers were in the range $\pm 0.8\%$. Further work is being undertaken to determine differences in cold periods and for extended time operations. Also, all instruments will be mounted on a single solar tracker in order to assure their exact alignment.

A comparison of 21 mean minute irradiances from two normal incidence pyrheliometers (B. Forgan)

2.2 The use of one or more normal incidence pyrheliometers to measure the direct mean solar irradiance over periods of a minute in the BSRN is dependent on their conforming to the uncertainty specification (initial BSRN requirement is 15 W/m^2 for a one minute exposure). A long series of data collected under operational conditions was available from two Eppley normal incidence pyrheliometers at Cape Grim, and these data have been analyzed to see whether BSRN accuracies can be met in the field. The basic data set for the analysis was derived by calculating 21 minute sample statistics. The long term average values suggest that the relative calibration of the two instruments remained stable within 0.3% - hence the uncertainty in the long term record is less than 0.5%. The mean ratio of the 21 minute averages during the period of the comparison is within 0.1% of the expected value, but this is significant at the 95% confidence level. The uncertainty of any ratio at this level is expected to be approximately 2.4%, representing a difference of 21 W/m^2 for the mean irradiance in the study. For one minute exposure, the uncertainty would be larger. Furthermore, given that the comparison with absolute radiometers shows that the 21 minute average can be in error by 2%, reaching the BSRN accuracy of 15 W/m^2 for a minute sample under clear sky conditions is unlikely for a single normal incidence pyrheliometer, or even for an average from more than one such instrument.

2.3 These results imply that an absolute radiometer should be used as the primary direct solar irradiance monitoring instrument. Given that the primary instrument will be off-line during calibration or during the shaded part of the measurement cycle, a thermopile pyrheliometer (e.g., normal incidence or similar continuously measuring device) should be employed to observe solar irradiance, with the thermopile reference temperature being monitored. The primary radiometer signal together with the thermopile pyrheliometer data can then be used to produce valid irradiance measurements and/or minute exposure data. In such a procedure, the absolute radiometer is effectively providing continuous calibration for the thermopile instrument.

Calibration of a normal incidence pyrheliometer (J. Olivieri)

2.4 Dr. Olivieri demonstrated the importance of turbidity on the accuracy of the calibration of a normal incidence pyrheliometer (in the same way that the temperature can influence the calibration factor), and how, using a sequential operation, it was possible to obtain measurements of irradiance closer to values from an absolute radiometer. After measuring the pyrheliometer signal, the calibration factor at the ambient air temperature (as a substitute for the pyrheliometer temperature) can be estimated and a first approximation to the direct normal solar irradiance obtained. The turbidity factor can then be estimated, which is used, in turn, to correct the originally measured pyrheliometer signal and hence to provide a more accurate value for the direct normal solar irradiance. Using this approach, values closer to those from an absolute radiometer have been obtained.

Error caused by circumsolar radiation in measuring global radiation as a sum of direct and diffuse components (G. Major)

2.5 As well as direct solar irradiance, pyrheliometers also measure some circumsolar sky radiation. On the other hand, diffusometers exclude a proportion of the circumsolar sky radiation together with the direct solar irradiance. Based on calculations in mean conditions and using a number of assumptions, Dr. Major noted the following:

(i) The deviations of normal incidence pyrheliometers from the cavity type absolute pyrheliometers could be several W/m^2 because of the effect of circumsolar radiation (ranging from 2 W/m^2 at direct radiation values of 1000 W/m^2 to 4-5 W/m^2 at values of 500-600 W/m^2).

(ii) The circumsolar difference between a pyrheliometer and a diffusometer is of the order of 1 W/m^2 and should be taken into account with the other error sources in high precision global radiation measurements.

(iii) If global radiation is measured by the "direct + diffuse" method, the best complementary readings of the two components could be expected if the distance between the diffusometer receiver and shading disk is chosen so that the slope angle is larger and the opening angle is smaller than those of the pyrheliometer.

Pyranometer errors (A. Ohmura)

2.6 As well as the known systematic cosine and azimuth errors in pyranometer readings, there is also a random error depending on the construction and exposure of the instrument (can be limited to less than 1% or of the order of 5 W/m^2 if the pyranometer is well built and maintained). For instance, the sensitivity of a pyranometer can change depending on the angle of tilt (this possibility should be checked when measuring surface albedo or reflected shortwave radiation using an inverted pyranometer). A detailed study of such effects is under way; experience with the Davos-type pyranometer shows a change of calibration coefficient of up to 2%.

IEA Longwave radiometer comparison at Hamburg (K. Dehne)

2.7 A comparison of six pyrgeometers and two pyrradiometers was carried out at the Meteorological Observatory, Hamburg in the period of August 1989 to March 1990. The reference "state-of-the-art" measurement of atmospheric thermal radiation could only be estimated from the results and deviations of the compared radiometers. The most demanding situation is when the "sky temperature" is much lower than the ambient air temperature and global solar irradiance is high (clear skies in summer around midday), the least demanding during overcast or foggy nights. Uncertainties in measurements were mainly linked to the quality of the instrument and its combination with a ventilation device and sun-following shading disk to screen direct solar radiation, accuracy of the calibration factors, and corrections for optical imperfections of pyrgeometer domes. If values affected by dew and rain were eliminated, the worst case maximum deviations in the radiometers compared were:

- half-hourly sums (around sunny noons) 15% (40 W/m^2)
- daily sums 8%
- decad means of daily sums 6%
- decad means of sums between 0930 and 1330 UTC 10%

The best case deviations (e.g. foggy nights) were 2% (5.6 W/m^2). However, these results depend on integration time and weather conditions during the relevant period. The long-term estimates are therefore specific for the comparison site and season and should not be regarded as an independent measure of the state of the art.

2.8 Based on the findings of this comparison, studies of calibrations, precision tests, etc., Dr. Dehne recommended a number of actions to reduce the uncertainties in atmospheric longwave irradiance measurements. In operation, radiometer domes must be ventilated to protect against dew and rime and heat exchange, the ventilation systems being tested to ensure non-interference with longwave measurements. Furthermore, the pyrgeometer dome should be screened by a sun-following shading disk. With regard to calibration, improved instrument-specific procedures must be developed, and results should be validated by field comparisons with reference radiometers. Computed values of atmospheric radiation during clear night hours used to determine instrumental longwave responsivity need to be checked against measurements by a reference radiometer. Another essential step is the development of a generally acceptable longwave reference radiometer; one instrument apparently having the potential to serve as such reference is the self-calibrating broad-band 2π-radiometer designed by F. Valero (NASA Ames Research Centre), although others could possibly be refined (e.g. the new "white" Eko- pyrgeometer in combination with a shading disk). Finally, Dr. Dehne urged that all new longwave radiometers (e.g. the Foot pyrgeometer) be carefully tested to assess their suitability for use as a BSRN field instrument. The correction term needed for dome temperature (as derived by Albrecht and Cox) for use in non-ventilated pyrgeometers must also be investigated, together with the requirement for an additional shortwave correction term.

2.9 The full report of the Hamburg comparison of longwave instruments will be available shortly and will be circulated by Dr. K. Dehne to all BSRN participants.

Analysis of pyrgeometer errors (J. Olivieri)

2.10 Dr. J. Olivieri presented a detailed analysis of errors in the measurement of longwave downward radiation using a "PIR" pyrgeometer, including the use of a revised Albrecht and Cox formula for correction of the effect of dome temperature (see also paragraph 2.8). A full account of Dr. Olivieri's analysis is attached as Appendix B.

Effect of non-uniform spectral dome transmittance on the accuracy of longwave measurements (F. Miskolczi)

2.11 Pyrgeometers, designed to measure longwave irradiance, are shielded by opaque material in the visible, whereas pyrradiometers, measuring total downward irradiance (visible and longwave), are shielded by polyethylene. Although deviations of sensor absorption characteristics from the ideal cosine law and the non-uniform absorptivity of the sensor coating are more or less taken into account in the design and calibration of the instrument, the effect of the protective dome on calibration and accuracy is less well understood. In particular, it is known that the transmittance characteristics of a polyethylene dome are strongly modified by ageing. Furthermore, the coincidence of strong atmospheric water vapour emmission lines with dome absorption lines can introduce a water vapour dependent error into radiation measurements.

2.12 Carrying out computations with a simplified instrument model, Dr. Miskolczi reached the following conclusions:

(i) In the case of Eppley domes (opaque), the effect of water vapour on calibration is small (less than 2%).

(ii) Because of the low effective dome transmissivity, the calibration of the Eppley instrument could be more sensitive to the wind.

(iii) The water vapour effect can be as high as 5% in the case of polyethylene domes.

(iv) There are large differences in transmittance of different domes of the same type (e.g. more than 20% in the case of Eppley domes, 2% in the case of polyethylene domes); instrument re-calibration is therefore essential when a dome is replaced.

(v) The ageing of a polyethylene dome changes instrument calibration by about 10%.

Pyrradiometer errors

2.13 Since pyrgeometers have problems of partial transmission of shortwave radiation (zenith-angle dependent) and of overheating of the silicon dome, study of errors in alternative measurements of longwave radiation using pyrradiometers is of considerable importance. Comparison of the Swissteco pyrradiometers at Payerne has revealed that an unshaded instrument normally underestimates the incoming longwave radiation, by 15-20 W/m^2 (but possibly up to 70 W/m^2 in some circumstances). However, if the dome is shaded and ventilated, the measured radiation in cloudless conditions can come to within 5 W/m^2 of the value computed using the LOWTRAN 7 radiation code and the in situ radiosonde profile. It is probably not practical to reduce the random pyrradiometer error to less than 5 W/m^2 - to do this requires development of new longwave instruments (e.g., the self-calibrating radiometer being developed at the NASA Ames Research Centre, or one based on a revised active cavity radiometer such as PMO-6 being built in Switzerland).

Workshop on physical characteristics of pyrgeometers

2.14 Under BSRN auspices, discussions on the physical characteristics of pyrgeometers (including pyrradiometers) took place at the headquarters of the Atmospheric Environment Service of Canada, Toronto, 29-30 April 1991, including BSRN scientists and representatives of instrument manufacturers. These instruments have been developed, for the most part, from pyranometer technology and for many years have been the basic workhorse for field experiments and monitoring projects world wide. Whilst the instruments seem to give an acceptable performance, many potential sources of error are apparent. Amongst those noted were:

- thermal gradients
- rapidly changing ambient air temperature
- adequacy of dome heating correction term
- visible light leaks
- variations in dome transmissivity
- differences in calibration methods
- differences in meteorological conditions
- dome emissivity
- heat conduction unknowns
- battery compensating circuit
- convection

(see also paragraphs above).

2.15 Efforts have been made to understand and correct for these factors and some modifications made to instruments but there are many outstanding questions on the validity and completeness of corrections. A practical absolute reference instrument does not yet exist, so absolute measurement uncertainty still remains to be quantified; there is speculation that this may be as high as 15%. The ultimate question to be answered is whether the physical design of pyrgeometers can be improved to reduce uncertainties to acceptable (quantifiable) levels.

2.16 The present workshop on the implementation of the BSRN endorsed the course of action discussed in Toronto, namely that radiation laboratories participating in the BSRN should undertake, as an organized consortium, a programme aimed at improving infrared instrument design and technology. As a first step, a task group of representatives of each laboratory will be formed to draw up the specific requirements for instrument development and to lay out a work plan (e.g. for undertaking necessary work at participating laboratories, involvement of private industry). A concern expressed was that improved design would raise the cost of instruments well beyond the present level, thereby limiting the number in field use with consequent impacts on private industry's willingness to contribute to the research and development required. Accordingly, trade offs between cost and performance should also be examined but avoiding any significant compromise in the desired accuracy limit. Sources of financial support for instrument development (and for purchase of possibly considerably more expensive instruments) must be identified and vigorously pursued.

2.17 Varying calibration techniques are employed for infrared instruments at different facilities. It was recommended that, at present, rather than trying to use a standardized calibration instrument uniformly throughout, a reference pyrgeometer from each facility be submitted for calibration at a central site. The need for a major effort aimed at the development and production of an absolute infrared radiometric instrument was reiterated (see also paragraph 2.8).

Proposal for BSRN broad-band infrared instrumentation comparison in the FIRE II cirrus experiment

2.18 Dr. J. DeLuisi described the plans for the BSRN broad-band infrared instrumentation comparison in concert with the FIRE II cirrus experiment, being conducted at Coffeyville, Kansas, U.S.A., 13 November - 7 December 1991. The comparison will be in parallel with the SPECTRE (SPECTral Radiation Experiment) aimed at providing high resolution spectral radiance measurements for validating model computations made in the framework of the WCRP/U.S. D.O.E. Intercomparison of Radiation Codes in Climate Models (ICRCCM). SPECTRE measurements will be accompanied by observations of trace gas profiles (water vapour, ozone, carbon dioxide, methane and chlorofluorocarbons) and use of lidar to detect the presence of cirrus.

2.19 The objective of the pyrgeometer-pyrradiometer comparison during FIRE II will be to determine the most representative method for broad-band measurement of downward longwave irradiance by:

(i) intercomparison of different instrument outputs;

(ii) comparison of instrumental measurements with values computed using state-of-the-art high resolution radiative transfer models and the observed atmospheric profile and composition, and with the concurrent high resolution infrared spectral observations from SPECTRE.

2.20 A number of BSRN scientists at the workshop expressed their willingness to participate and to provide instruments for inclusion in the FIRE II intercomparison. The workshop recommended that this intercomparison be recognized as the first formal project of the consortium of BSRN laboratories studying the improvement of infrared instrumentation (see paragraph 2.16). Moreover, participating scientists (from Australia, Canada, France, Germany, Israel, Switzerland) will form a BSRN sub-group responsible for planning the intercomparison and subsequently assembling and reviewing the results.

3. RECOMMENDATIONS FOR DETERMINATION OF BASIC BSRN PARAMETERS AND BSRN OPERATIONAL PROCEDURES

Following the results presented above, the workshop discussed in detail recommendations for the determination of basic BSRN parameters and a number of BSRN operational procedures. These recommendations are partially based upon knowledge of the accuracies and characteristics of presently available instrumentation, and how they can best be used to approach as nearly as possible BSRN requirements. Some BSRN stations may well not initially possess some of the more expensive equipment such as an absolute radiometer or an adequate solar tracker. The proposals are not meant to exclude such stations, but to provide guidelines for attaining the measurement quality that appears feasible. Measurements produced at the limit of the state-of-the-art will enable the assessment of uncertainties to be refined, and permit overall improved confidence in the values produced. Measurements of the highest accuracy of surface radiation terms are also indispensable in detecting global change signals. The cost of fully equipping a BSRN station in the way described below is very small compared to the cost of satellite observing systems (for which BSRN will provide essential ground truth) as well to the cost of other meteorological observing systems.

3.1 Instruments and methods

Direct solar irradiance (I)

3.1.1 The target accuracy for measurement of direct solar irradiance in the BSRN is 1% (or 2 W/m^2 as the acceptable maximum deviation from the "true" value). For the continuous measurements used in providing the mean value over 1,2,3 or 6 minutes (see section 3.3 - Data acquisition), a normal incidence pyrheliometer (NIP) or similar is recommended. Since the noise level of such, an instrument is too high to satisfy BSRN requirements for direct solar irradiance measurements (see paragraphs 2.2, 2.3), an absolute radiometer shall be used in parallel to "calibrate" the NIP quasi-continously (every 5-60 minutes if I $>$ 400 W/m^2). The absolute radiometer must have the same window as the NIP (quartz, suprasil W) to ensure equivalent operational characteristics.

3.1.2 A solar tracker with an accuracy of $\pm 0.1^{\circ}$ is needed to accommodate the NIP, the absolute radiometer and, during calibrations, a second absolute radiometer. The solar tracker shall have a four-quadrant sensor monitoring the pointing continously (same sampling rate as the NIP).

3.1.3 The parameters to be monitored are: output of NIP thermopile; outputs of absolute radiometer (U,I or thermopile signal for a passive instrument); body temperatures of the NIP and absolute radiometer; output of the four-quadrant sensor.

3.1.4 Outstanding questions to be investigated are:

(i) influence of window on measurement and calibration (the irradiance must be integrated over the whole spectrum, not just over the range of the quartz transmittance); a correction table for window effects should be developed;

(ii) development of possible corrections for temperature, turbidity and water vapour dependence for NIP measurements (based on analysis of AES data);

(iii) improvement to NIP measurements by using a field-of-view angle of 5° instead of 5.7° to reduce the turbidity dependence.

Diffuse radiation (D)

3.1.5 BSRN target accuracy is 4% (5 W/m^2). The pyranometer to be used shall be ventilated and have a body temperature sensor (PSP, CM11 or similar). For shading from direct sun, a tracking disk is needed with the same field of view as the absolute radiometer (5° full angle from the centre of the detector) and always shading the dome completely.

3.1.6 Parameters to be acquired are: output of pyranometer thermopile; pyranometer body temperature.

3.1.7 Outstanding questions to be investigated are:

(i) influence of optical properties of domes (WG295, Schott K5, etc.) on measurements and calibration;

(ii) influence of different available ventilation systems and determination of maximum power/heating of ventilation system.

Global radiation (G)

3.1.8 BSRN target accuracy is 2% (5 W/m^2). Although the global radiation may be determined as a sum of direct and diffuse irradiance, a direct measurement shall be made with a ventilated pyranometer (same instrument type as for diffuse radiation) in order to provide a basis for quality control and calibration boot strapping (see section 3.2 - Calibration procedures).

3.1.9 Parameters to be acquired: output of pyranometer thermopile; pyranometer body temperature.

Reflected shortwave radiation (R)

3.1.10 This measurement, required at BSRN stations undertaking the "expanded measurement" programme, shall be performed using the same type of ventilated pyranometer as for diffuse and global radiation. A horizontal shadow band is needed to protect the instrument dome from direct solar radiation at low solar elevation. The angle sustained shall be less than 5° (i.e. covering nadir angles 85° to 90°).

3.1.11 Parameters to be acquired: output of pyranometer thermopile; pyranometer body temperature.

3.1.12 An outstanding problem to be studied is assessment of the minimum height for measurements in order to guarantee representativeness (may depend on nature of site). The NOAA tower in Boulder has recently been instrumented to investigate this question.

Downward longwave radiation (A)

3.1.13 BSRN target accuracy is 5% (10 W/m^2). Downward longwave irradiance shall be measured with a shaded and ventilated pyrgeometer and pyrradiometer (using a shading device as for measurement of diffuse solar irradiance). At present, it seems that only the "PIR" pyrgeometer (Eppley) with a dome temperature sensor (but without a battery circuit) can meet BSRN requirements. For pyrradiometers, the quality shall be comparable to the pyranometers used at the site. The shortwave and longwave calibration of the pyrradiometer must not deviate by more than 2%.

3.1.14 Parameters to be acquired are: outputs of pyrgeometer and pyrradiometer thermopiles; instrument body temperatures; dome temperature of the pyrgeometer.

3.1.15 A number of outstanding questions need to be studied:

(i) Influence of the dome optical properties on calibration and measurement including changes in spectral distribution due to water vapour content and the use of black body radiation for calibration; the calibration temperature must be agreed.

(ii) Influence of different ventilation systems.

(iii) System of measurement of dome temperature.

Upward longwave radiation (E)

3.1.16 This measurement, required at BSRN stations undertaking the expanded programme, shall be performed with the same type of ventilated pyrgeometer and pyrradiometer as used for observing the downward longwave irradiance. As for measurement of reflected shortwave radiation, a horizontal shadow band is needed to protect the instrument dome from solar radiation at low solar elevation. The angle sustained shall be less than 5° (i.e. covering nadir angles 85° to 90°).

3.1.17 Parameters to be acquired are outputs of pyrgeometer and pyrradiometer thermopiles and instrument body temperatures.

3.1.18 Problems to be investigated include:

(i) Assessment of height for measurements to guarantee representativeness (depends on water vapour profile close to surface).

(ii) Possibility of determining the upward longwave radiation by small angle radiometers or infrared temperature sensors (e.g. PTR5).

Summary of instruments used at a BSRN station

3.1.19 For operational use, it is recommended that a BSRN station should have available the following complement of instruments (including spares):

- 1 absolute radiometer

I - 2 normal incidence pyrheliometers (1,1 spare)

D,G - 3 pyranometers with ventilation system and shading device (2,1 spare)

R* - 2 pyranometers with ventilation system and shading device (1,1 spare)

A - 2 pyrgeometers with ventilation system and shading device (1,1 spare**)
- 2 pyrradiometers with ventilation system and shading device (1,1 spare**)

E* - 2 pyrgeometers with ventilation system and shading device (1,1 spare**)
- 2 pyrradiometers with ventilation system and shading device (1,1 spare**).

* Parameter only included in expanded measurement programme.

** Spare also used as "standard" (see section 3.2 - Calibration procedures).

3.2 Calibration procedures

Absolute radiometer for direct solar irradiance

3.2.1 The operational absolute radiometer shall be calibrated against an absolute radiometer traceable to the World Radiation Reference every six months. No more than three steps shall be involved in the traceability which should be documented in detail.

Pyranometers for diffuse and global radiation

3.2.2. The pyranometers used for measuring diffuse and global radiation shall be calibrated by the composite method starting with a tentative value for diffuse radiation (to be fully described in the BSRN operations manual - see section 3.5). At the sites, instruments are exchanged periodically (diffuse → global, global → diffuse) at the solar solstice. Moreover, the instrument measuring global radiation should be shaded and unshaded from time to time during clear and overcast sky conditions to check the measurement of diffuse radiation and evaluate the pyranometer performance (e.g. cosine response, temperature coefficient). The six months of data from the pyranometer measuring global radiation will provide a basis for determining if corrections have to be applied when it is used for measuring diffuse radiation. The ratio of the calibration for clear and overcast skies shall lie in the range 0.99 to 1.01 (method of calibration to be fully described in the BSRN operations manual).

3.2.3 An outstanding task is to determine standard sky radiance distribution functions for clear and overcast conditions to be used in ascertaining the diffuse calibration factors.

Pyranometer for reflected radiation

3.2.4 Basic calibration is by the composite method with the sun as a source but operating as a diffuse instrument. In order to assess the effect of using the instrument in an inverted position, a test with an integrating sphere is recommended

Pyrgeometers and pyrradiometers for longwave radiation

3.2.5 Current methods of calibration now yield divergent results and thus no single method can be recommended until the reasons for differences are fully understood. It is therefore proposed, ad interim, that the manufacturer's calibration factor be used for the "PIR" pyrgeometer. Assuming that PIR calibration factors are reasonably constant over time, a posteriori corrections could be made whenever a standard BSRN method is agreed. Temperature sensors shall have an accuracy of 0.1K and must be calibrated individually.

3.2.6 Pyrradiometers shall be calibrated for shortwave and longwave separately, the former by the composite procedure, the latter with one of the existing methods. However, an exactly reproducible method should be chosen in order to allow for a posteriori correction when a standard BSRN procedure is agreed.

3.2.7 The calibration of the field instruments shall be checked every six months against a "standard" pyrgeometer and pyrradiometer, maintained as station spares, which are themselves checked annually at a Radiation Centre.

3.2.8 As is apparent from several parts of the preceding text (e.g. paragraphs 2.8, 2.14, 2.17, 3.2.5), the calibration of longwave instruments is a major outstanding problem and different calibration techniques must be analyzed urgently in order to understand the physical reasons for the different results obtained (e.g. influence of type of black body, calibration temperature) and the variance and/or repeatability of the various methods. Based on this analysis, a recommendation for a single unified technique should be developed.

3.3 Data acquisition

3.3.1 The workshop laid down requirements for what it saw as the "ideal" data acquisition system namely, production of one minute averages for all basic BSRN parameters. However, it was recognized that not all BSRN stations would be able to operate according to this scheme from the inception of data collection, and it was agreed that data sampling at intervals of 1,2,3 or 6 minutes, depending on station capability, would be acceptable in an initial phase up to 1 January 1996. After this date, minute samples would become the strict BSRN standard. The data values shall be the means over the sampling period, starting on the hour (UTC). For data not delivered as one-minute means, the additional requirements in the following paragraphs can be adapted accordingly.

Data acquisition system

3.3.2 The data acquisition system shall allow for a sampling of each channel once per second or faster. Analogue signals shall be filtered (integrated) to provide one second samples. The accuracy of the system (DVM, scanner, cabling) shall be $\pm 0.01\%$ of the reading or $\pm 1\,\mu V$ whichever is the greater.

If this accuracy is not sufficient for the resolution of a given channel, a high quality pre-amplifier will have to be used.

On-site data evaluation

3.3.3 From the one-second data samples, the mean, standard deviation, maximum and minimum will be calculated and included in the raw station (Level I) data (the one-second readings need not necessarily be stored). For parameters for which instantaneous values are required, the last value (e.g. SPM readings) or the mean of the last ten seconds (e.g. for normal incidence pyrheliometers or absolute radiometers) should also be stored. In this context, the quasi-continous calibration of the NIP is performed using the last ten readings of the basic period, the timing of the absolute radiometer being adjusted accordingly. The electrical calibration of an absolute radiometer will take one or two minutes with readings of irradiance for the last ten seconds of the relevant minute interval becoming available after a further minute. The mean direct solar irradiance can then be calculated and compared to the corresponding mean value produced by the NIP, so providing an instantaneous calibration factor.

3.3.4 It remains to define detailed data evaluation procedures to obtain the mean, standard deviation maximum and minimum for each parameter. The format for BSRN site-to-archive file format is defined in the data management plan (see section 4).

3.4 Measurement uncertainty techniques

3.4.1 Dr. C. Wells reviewed progress in developing measurement uncertainty techniques for application to the BSRN. A document is being prepared summarizing the basic methodology including definition of the "true value" in the BSRN context, the type of errors that could arise, outlining uncertainty models and their application to calibration of solar radiometers and to evaluating the validity of field measurements. The power of this approach lies in providing estimates of measurement uncertainties that it has not so far been able to quantify accurately.

3.4.2 Participants in the workshop were impressed with the prospects offered by the application of these techniques and looked forward with interest to seeing Dr. Wells' document. It was agreed that a uniform method of performing measurement uncertainty analysis throughout the BSRN would be a valuable contribution enabling deeper understanding of errors in the measurements (random and systematic) and better assessment of errors, leading eventually to improved accuracy and basis for developing refined instruments.

3.5 Preparation of operations manual for the BSRN

3.5.1 Dr. B. McArthur reported on progress in the preparation of an operations manual for the BSRN. At the first workshop on the implementation of the BSRN (Washington, December 1990), the proposal was that extensive use would be made of existing manuals and documentation on radiation instrumentation (e.g. WCRP Publication Series No. 7 - Revised Instruction Manual on Radiation Instruments and Measurements) and a number of other manuals prepared for national use. However, a major hindrance to assembling a BSRN manual had been the many outstanding questions regarding the manner in which fluxes were to be measured and details of the way instruments were to be used. Most of these questions had been resolved during the discussions at the present meeting (see sections 3.1 - 3.3) and it should therefore now be possible to complete the BSRN operations manual fairly rapidly.

3.5.2 Dr. McArthur suggested that a convenient way to proceed would be to make up a three volume manual. The first volume would be simply the WCRP Publication Series No. 7. The second volume would consist of a combined, revised and supplemented version of the International Standards Organization documents ISO/DIS 9060 - Solar Energy, Specification and Classification of Instruments for Measuring Solar and Direct Solar Radiation and ISO/TR 9901, Solar Energy - Field Pyranometers - Recommended Practice for Use, and the IEA Task 9F draft document - Measurements of Shortwave Irradiance intended for use in Testing Solar Converters. These would be complemented by documentation on the care and maintenance of instruments measuring direct beam radiation and incoming infrared radiation and a description of specific on-site quality assurance techniques. Information on site selection, supporting measurements (e.g. basic meteorological observations), and instructions for operating specific types of instruments only found at selected stations (e.g. sunphotometers, microwave radiometers) would also be included. The third volume would deal with the maintenance, calibration and operation of the data acquisition system. Overall, the manual would be written for a skilled technologist with some experience in the measurement of radiative fluxes and computer programming.

3.5.3 It was considered that these three volumes together would establish a suitable basis for BSRN operations. The WCRP document described the basis of radiation measurements and provided valuable background material but was too general and complex for a day-to-day reference. The ISO and IEA documents were short and concise descriptions of pyranometers and pyrheliometers and their operation but did not include details on measurement of direct beam and infrared radiation and would need to be supplemented with additional documentation as discussed above.

3.5.4 Dr. B. McArthur was asked to proceed to draw up a draft BSRN operations manual on the lines described and to circulate the draft to BSRN participants as soon as possible.

4. BSRN DATA MANAGEMENT

4.1 Data management plan

4.1.1 The contents of a preliminary version of a technical plan for BSRN data management prepared by the World Radiation Monitoring Centre (WRMC), Division of Climate Research, Department of Geography, ETH, Zurich (in collaboration with the Surface Radiation Budget Project Satellite Data Analysis Center, NASA Langley Research Center, Hampton, VA, USA) were reviewed. The technical organization of the data base being planned at the WRMC was considered to be excellent but it was recommended that more descriptive information concerning the data flow be included. In addition, the functions and responsibilities of the different elements in the data management system needed to be decided at the present meeting (see section 4.7). The principal contact points within each element should also be identified, and schedules for delivery of data and information from participating sites to the WRMC, the amount and type of data included in each shipment and other details of data acquisition, processing exchange and archiving specified.

4.1.2 It was also recommended that the form of the BSRN data management plan should be similar to those for other other WCRP projects (e.g. the International Satellite Cloud Climatology Project). Following the various additions/revisions suggested, the BSRN data management plan will be published in the WCRP "white cover" series for appropriate circulation and allowing for possible future updates.

4.2 The BSRN data set

4.2.1 The following surface radiation data will be provided by observing sites to the WRMC:

- direct solar irradiance (I)
- diffuse solar irradiance (D)
- global solar irradiance (G)
- reflected shortwave radiation (R) (expanded measurement programme only)
- downward longwave radiation (A)
- upward longwave radiation (E) (expanded measurement programme only)

(see section 3.1).

Ideally, one minute samples should be provided for all basic BSRN parameters but samples at intervals of 1,2,3 or 6 minutes, depending on station capability, would be acceptable in an initial phase up to 1 January 1996 (see paragraph 3.3.1). As noted in paragraph 3.3.3, the mean, standard deviation, maximum and minimum values in the sampling interval will be stored.

Information on instrument uncertainties/characteristics should be included as required in the BSRN site-to-archive file format (specified in the BSRN data management plan).

4.2.2 As regards the supporting meteorological surface and upper air observations obtained in the vicinity of the station, the following are required for inclusion in the composited BSRN data set for each station:

- twice daily radio-sonde soundings (00, 12 UT)
- surface (SYNOP) reports at three-hourly intervals

It was noted that, in some cases, nearby surface stations may report observations only for daylight hours and, in other cases, a BSRN station may not be located near either a surface and/or upper air station. The workshop emphasized the importance of concurrent, co-located surface and upper air data as a complement to BSRN radiation measurements. Nonetheless, data from any station which could undertake radiation measurements to BSRN standards would still be of considerable value. It was suggested that sites providing radiation and co-located meteorological data be designated "fully equipped" BSRN stations, other sites as "radiation only" BSRN stations. The workshop requested that this point be brought to the attention of the WCRP Working Group on Radiative Fluxes. Advice on the need for SYNOPS and/or radio-sonde reports to be made simultaneously with satellite overpasses should also be sought, although it was pointed out that it was unlikely to be feasible, given the economic constraints, to provide these observations at other than standard times except for special short test periods.

4.2.3 Stations with an expanded measurement programme will provide additional information for satellite algorithm improvement, including particularly refined data on ozone and water vapor vertical profiles, cloud base height, aerosols, etc.

4.2.4 The BSRN data set will be fundamental input for derivation of a global surface radiation budget climatology by the Satellite Data Analysis Center (see section 6). These global fields will be available to the BSRN research community, but will not be included in the BSRN data archive for the time being.

4.3 Station data collection and transfer to WRMC

4.3.1 Each BSRN station shall accumulate data in one month batches for shipment to the WRMC. A delay of up to three months in despatch of data to the WRMC from the station would be allowed for local quality control, data processing and recording the data in the required format on an appropriate medium (e.g. floppy disk, magnetic tape). Up to three monthly batches (as separate files on the magnetic medium selected) could be shipped at one time.

4.3.2 Each participating BSRN station is responsible for ensuring that the most complete set of supporting surface and upper air meterological data (see paragraph 4.2.2) is also shipped periodically (in delayed mode) to the WRMC. Detailed arrangements for obtaining these data shall be developed by each BSRN station/centre with their respective national meteorological services.

4.3.3 The WRMC is responsible for collecting data from participating BSRN sites, carrying out appropriate quality control to ensure data integrity, for producing the composite BSRN data set, for archiving and distributing data (see section 4.4). Copies of available data will be distributed to each of the participating BSRN stations.

4.4 Data archiving and distribution

4.4.1 Although in principle there would no longer be a requirement to save raw data at the station level once the various radiation quantities had been computed and the data delivered of the WRMC, several participants in the workshop emphasized the possible need to recompute various quantities because of inadvertent errors introduced by unknown instrument shortcomings, bad data, faulty algorithms, software to format the data for transfer to the WRMC. It was therefore, recommended that each BSRN station/centre retain the original raw data (including such parameters as dome and ambient instrument temperatures, wind speeds, etc.) <u>for a minimum period of ten years</u> after the measurement has been made.

4.4.2 The WRMC will make available copies of the composited BSRN data set to all BSRN participants. The composited data set will be provided to the NASA Langley Research Center (in its capacity as Satellite Data Analysis Center) within a time delay of 1-2 years. Data will not be distributed to "external" users until at least the first full year of BSRN data has been assembled, validated and evaluated by the Scientific Evaluation Panel (see section 4.5). After this, the data will be generally available and will also be passed to other archives such as the World Radiation Data Centre, Leningrad; EOSDIS/DAAC, Hampton, Virginia; the Asheville National Climate Data Center.

4.5 Scientific Evaluation Panel

4.5.1 Quality control will be applied at many different stages in the BSRN, from the instrumental level on site to data archiving at the WRMC. Final evaluation of data quality and integrity will be the responsibility of the "BSRN Scientific Evaluation Panel", composed of representatives of each participating BSRN site, the World Radiation Centre at Davos, the WCRP Working Group on Data Management for Radiation Projects, the Satellite Data Analysis Center, a metrologist and the WCRP modelling community (representative to be proposed by the Director, WCRP).

4.5.2 It was recommended that the Panel first meet immediately after production of the first year of BSRN data, in order to make a careful assessment of the quality of the BSRN data set. Thereafter, meetings of the Panel should take place annually.

4.6 BSRN status reports

4.6.1 The workshop recommended that periodic reports on the status of the BSRN be prepared and distributed for the information of participants in the BSRN project, for scientific administrators and managers, and for publicizing the project. Representatives of the WRMC and the WCRP were requested to work-out details of the format of the publication, the information to be included, the schedule for production, arrangements for preparation of the report and its distribution. It was noted that (quarterly) status reports are produced in respect of the International Satellite Cloud Climatology Project and Global Precipitation Climatology Project.

4.6.2 The workshop recalled that publication of two "technical" BSRN documents is foreseen (operations manual - see paragraph 3.5.4 and data management plan, 4.1.2). The workshop also reiterated the suggestion made at the earlier workshop in Washington that brochures to advertise the concept and implementation of the BSRN be prepared in order to attract essential scientific support and resources required to establish and maintain the network. Likewise, articles on the BSRN should be submitted to the Bulletin of the American Meteorological Society, WMO Bulletin, etc.

4.7 Summary of BSRN elements and responsibilities

The tasks to be carried out and responsibilities of the different elements of the BSRN (national site/centre, WRMC, Scientific Evaluation Panel) with respect to measurement, calibration, quality control, data handling, etc. are summarized in Table I.

4.8 Data system test

It was agreed that all sites ready or on the verge of being able to undertake BSRN measurements should participate in a data system test between September 1991 and March 1992. Details of the test will be finalized between BSRN station representatives and the WRMC.

Table I - BSRN elements and responsibilities

BSRN site/centre	WRMC	Scientific Evaluation Panel
- Maintain calibration of station standard instruments (absolute radiometer-para 3.2.1, pygeometer and pyrradiometer-para 3.2.7)	- Insertion of site data and quality control information in BSRN data base	- Review of BSRN instruments and measurement techniques
- Site calibration of all instruments	- "Conversation" with site (queries on data submitted, response to site queries)	- Official review (qualification) of BSRN annual archive
- Site measurements and local data acquisition/storage	- Distribution of composited BSRN data to sites and to SDAC	- Keep under review scientific basis/ justification for BSRN activities
- Local quality control	- Update, maintain and safeguard BSRN archive	- Identify problems and propose solutions
- Regular submission of monthly batches of data to WRMC	- Organize annual session of scientific Evaluation Panel and submit annual report on BSRN data collection, quality, archival to Panel	
- Response to queries from WRMC		
- Re-evaluation/re-processing of station data if necessary	- Distribution of final BSRN (annual) data to users, the World Radiation Data Center and other archive centres (on request)	
- Representative of station to participate in annual session of Scientific Evaluation Panel		

5. REPORTS ON BSRN STATION IMPLEMENTATION

5.1 Several participants gave presentations on the implementation of BSRN stations in their home countries. Important points/developments are summarized below.

Switzerland

5.2 The existing station at Payerne is being adapted for operation as a BSRN station including use of a 30m mast. Although the sampling time at present is ten minutes (in accord with that in use in the network of Swiss automatic stations), this will be changed to one minute (involving major modifications to the data acquisition system and software).

Canada

5.3 Two Canadian BSRN stations are planned. The first, the RAGS Observatory, Asquith, Saskatchewan, has been operating in a non-standard mode for the last two years. Both the data acquisition system software and instrumentation require upgrading to meet BSRN standards and to provide the basic set of BSRN measurements. A co-located automatic weather station will provide temperature, pressure, humidity, wind direction and speed. A synoptic station is located at a distance of about 35 km (Saskatoon Airport). The second Canadian BSRN site will be at the Eureka Arctic Ozone Observatory, being constructed during 1992 and becoming operational by 1993 (BSRN measurements from end of 1993). The Eureka Observatory is within 16 km of the Eureka SYNOP and radio-sonde station. Ozone and spectral infrared radiation will also be monitored at the Eureka Observatory. The overall time frame for the operation of both these stations is dependent on the progress of funding proposals presently before the Science Advisor of the Atmospheric Environment Service.

Germany

5.4 It has now been decided that Lindenberg will be implemented as a BSRN station in Germany (instead of Schleswig). Lindenberg (WMO station 10393, latitude 53.22°N, longitude 14.2°E, height 98 m) is a long-standing meteorological station with four radio-sonde soundings per day and is manned continously. Up to now, it has only undertaken limited radiometric activities but steps are being taken to procure the appropriate equipment. As for Georg von Neumeyer, instruments will be installed in the Antarctic summer (i.e. end of 1991) and the station should be operational from March 1992. However, for obvious logistic reasons, delivery of data will be annually. The station in Spitzbergen (Ny Alesund, to be operated jointly by Germany and Norway), is also expected to become operational by 1992.

U.S.A.

5.5 Of the five proposed (USA/NOAA) sites (Barrow, Alaska; Boulder, Colorado; Bermuda; Kwajalein, Marshall Is; South Pole), the extent to which BSRN standards can be implemented will depend on current and future funding.

Although the time sampling interval for the various measurements will become three minutes within the next few months, no new instrumentation able completely to satisfy BSRN requirements (e.g. as specified at this workshop) is expected to be brought on line during the next year. A test data set including data from several of the U.S.A. stations has been submitted to the WRMC but did not include the co-located meteorological data (although all the planned sites are near standard meteorological stations including upper air soundings in their programmes).

Australia

5.6 The planned station at Alice Springs should be operational by the beginning of 1992. However, economic constraints have led to investigation of cheaper instrument mountings and to study of development of a cheaper active tracking system.

Egypt

5.7 The Aswan environment is a typical sub-tropical arid and desert area (sandy surface with abundant granite rocks). The existing measurement programme includes global, diffuse and direct solar radiation, downward atmospheric radiation, UV and ozone. However, only hourly measurements are possible at present. To be able to meet BSRN requirements, the station has need for a pyrgeometer (PIR) with temperature response in the range of -20°C to +50°C, a data acquisition system (to include records of instrumental temperature, etc.), appropriate computing resources (e.g. IBM-type personal computer).

U.S.S.R.

5.8 Under the leadership of the World Radiation Data Centre, Main Geophysical Observatory, Leningrad, it has been agreed that it will be more suitable to install and operate a BSRN site at the field station at the Voejkov Observatory near Leningrad (latitude 59.98°N, longitude 30.30°E) instead of in Franz Josef land as suggested at the Washington workshop. Actinometric observations have been carried out the Voejkov Observatory continously since 1952 and personnel would be available to undertake measurements according to BSRN standards. However, improved instruments are needed together with an appropriate data acquisition system, processing facilities, modem, etc. Because of severe financial constraints it is not possible for the Main Geophysical Observatory to purchase the necessary equipment, and support through other channels is needed. In summary, the instruments and devices required are:

- normal incidence pyrheliometer with sun-tracker (1 or 2)
- infrared radiometer (or pyrgeometer)
- data acquisition system
- IBM-type PC
- modem

Estonia

5.9 Concerning the implementation of the BSRN station at Toravere, the current situation is that hourly sums of direct, diffuse, reflected and global solar radiation as well as the net radiation are being measured. The longwave balance is determined from the measurement of net radiation, taking into account cloud/weather conditions. (A full meteorological observation is taken every six hours, partial every three hours). Additional features of the station programme are verification of global radiation using a luxmeter and a 32m observation tower permitting measurements of the gradients of radiative fluxes (and other meteorological parameters) at six different levels. The station pyrheliometer (Yanishevsky M59) is calibrated against the U.S.S.R. reference at least once every three years and a secondary reference actinometer and pyranometer are used in making routine checks at least once a month. The station is fully staffed with highly qualified personnel. In order to meet BSRN project requirements, a PC-type computing facilities and (graphics) printer are needed together with a much improved data acquisition system (data logger with at least 16 analogue inputs in the range $\pm 10\,\mu V$, and 8 digital counter inputs for wind measurements), but economic restraints are preventing acquisition of the necessary equipment. (The Toravere station operates under the auspices of the U.S.S.R. State Hydrometeorological Committee but theoretical and technical support is provided by the Institute of Astrosphysics and Atmospheric Physics of the Estonian Academy of Science).

Venezuela

5.10 The workshop was gratified to hear the interest of the Department of Hydrology and Meteorology of the Ministry of the Environment and Renewable Natural Resources of Venezuela in participating the BSRN project. Three important potential sites that could be offered are La Orchila Island (Caribbean Sea), Pico Espejo (Andes), and Quibor (subject to agreement of the National Solar Radiation Sub-commission of Venezuela). At present, Venezuela has an active solar radiation measurement programme (146 stations) and participated in the first WMO regional pyrheliometric comparison in RA-IV (April 1989). Technical support and advice will be required in order to initiate the necessary longwave measurements and assistance in acquiring instrumentation for this purpose.

Brazil

5.11 Implementation of the station at Florianopolis is proceeding, assistance on a bi-lateral basis being provided by Germany. Substantial assistance will be required for the implementation of a BSRN station at Manaus. Professor S. Colle is establishing co-operation with the Brazilian National Meteorological Service in this regard, and various possibilities for obtaining support will be explored.

Hungary

5.12 At the Budapest-Lorinc station, all measurements will be made to BSRN standards, the only limitation being the solar tracker (one only, not computer-controlled). An automatic data acquisition system is in place, sampling at a rate of several times a second. However, some concern is felt about the environment of the station which is not uniform and could be adversely affected by the city of Budapest itself. Assistance would be required to set up a BSRN station elsewhere in Hungary with a better environment.

Norway (Scientific Expedition to the Arctic Ocean)

5.13 As part of the Nansen Centennial Arctic Programme, Norway is planning an Arctic Ocean scientific expedition for the period of 1993 - 1995, providing an opportunity to obtain surface radiation flux measurements and information on Arctic clouds in a marine Arctic environment removed from the influence of land masses. It would be of major scientific interest to be able to include in the BSRN data base measurements from a ship in the Arctic Ocean if only for a period of a year or two. Technical aspects of instrumentation and ship-borne installation, as well as possibilities for acquiring the necessary instruments will be discussed between Dr. J. DeLuisi (BSRN Project Manager) and Dr. T. Vinje (Norwegian Polar Institute).

Summary of implementation status

5.14 Four sites (Alice Springs, Australia; Payerne, Switzerland; Boulder, USA; Carpentras, France) are expected to begin formal BSRN operation, collection and submission of data according to BSRN standards from 1 January 1992. As mentioned in several of the above reports, economic contraints seem likely to delay full implementation to BSRN standards for the first few years of operations in some countries.

6. PROGRESS IN SURFACE RADIATION BUDGET ESTIMATIONS FROM SATELLITE DATA AND SURFACE MEASUREMENTS

6.1 Dr. C. Whitlock (Satellite Data Analysis Center, NASA Langley Research Center, Hampton, Virginia, USA) described progress in estimating surface radiation budget components from remotely sensed data. However, he emphasized the importance of surface radiation measurements to validate these estimates both during the development/tuning of the satellite data algorithms and for checks during the production phase (as characteristics of satellite instruments often change with time). Algorithms will also be kept under constant review and could be subject to modification to bring results into line with accurate ground truth measurements.

6.2 There has been significant progress in obtaining global estimates of the shortwave radiation climatology. A large amount of surface solar radiation data are available from the World Radiation Data Centre, Leningrad, which have been used as a basis for selecting the shortwave algorithms for global processing of satellite data. Four such algorithms using ISCCP top-of-the-atmosphere radiances to estimate surface shortwave irradiance have been examined at the Satellite Data Analysis Centre. Comparing monthly mean results with Leningrad data showed that two of the methods gave rms errors (including bias) of less than 25 W/m^2, while two others showed rms errors of more than 50 W/m^2, with large data gaps. These last two algorithms have been returned to the originating scientists for revision and for possible use at a later date. In the meantime, initial global processing to produce surface shortwave fluxes has begun with the two more accurate algorithms. Estimates of monthly broad-band shortwave surface albedo and net surface irradiance as derived from satellite data have also been examined but there is, at present, very little data on the scale of 250 x 250 km^2 against which these estimates can be validated. It is hoped that BSRN data could go some way to filling this gap.

6.3 Estimates of surface longwave irradiance derived from satellite data are far from being in a satisfactory state. Two major problems existed. First, temperature, pressure, precipitable water and cloud height data from TOVS are not accurate enough as input to longwave algorithms, this assessment being based on comparison of TOVS data with concurrent meteorological observations from FIRE Phase I (Wisconsin, October 1986). Secondly, the absolute accuracy of measurements of the surface longwave irradiance being used as ground truth is uncertain. It was an urgent requirement for the BSRN to investigate and quantify the accuracy of existing measurements. This information is regarded as essential by the community of scientists working with satellite algorithms in order to develop further and validate new methods of estimating the global distribution of downward longwave irradiance (e.g. approaches based on using operational meteorological analyses in combination with satellite measurements).

7. FUTURE ACTIVITIES

7.1 The Project Manager, Dr. J. DeLuisi, and representative of WCRP were asked to take steps towards organizing the numerous actions identified at the workshop, in particular consideration of requirements for development of longwave instrumentation by laboratories participating in the BSRN (paragraphs 2.16 and 2.17), the broad-band longwave instrumentation comparison in the FIRE Phase II Cirrus Experiment (paragraphs 2.18 - 2.20), investigation of the outstanding questions on BSRN instruments and methods (section 3.1), calibration procedures (section 3.2), on-site data evaluation and quality control (section 3.3). The BSRN operations manual and data management plan needed to be finalized (paragraphs 3.5.4 and 4.1.2) and ways of assisting implementation of various BSRN stations (see section 5) must be explored.

7.2 The workshop considered that a further meeting like the present should not be necessary in the near future and most questions could be dealt with by correpondence. However, it was agreed that the Project Manager should occasionally call together selected groups of BSRN participants to consider specific questions (e.g. representative of laboratories interested in the development of longwave instrumentation and/or organization and review of results from comparison of longwave instrumentation in the FIRE Phase II Experiment). In due course, outstanding BSRN questions would also be taken up by the Scientific Evaluation Panel (see section 4.5). If required, a full BSRN workshop could be convened in about two years time.

8. CLOSURE OF WORKSHOP

The second workshop on the implementation of the WCRP Baseline Surface Radiation Network was closed at 1600 hours on 9 August 1991. The workshop reiterated its gratitude to Dr. C. Fröhlich and the staff of WRC/PMOD for their support and assistance in hosting the workshop. Following closure, a small group of BSRN scientists met to finalize plans for the November FIRE II pyrgeometer intercomparison (see paragraphs 2.18 - 2.20).

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MEASUREMENT OF LONGWAVE DOWNWARD IRRADIANCE USING A "PIR" PYRGEOMETER

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1. The Albrecht and Cox "revised" formula

Currently, use is made of the 1974 and 1977 Albrecht and Cox formula:

$$L(\downarrow) = \frac{E}{\eta} + \varepsilon_c \sigma T_c^4 - k\sigma(T_d^4 - T_c^4) \qquad (0)$$

with the emissivity $\varepsilon_o = 1$
and $k = 4$

This formula gives good results, but must be considered "semi-empirical" because of the "k" coefficient, which is determined experimentally.

In this paper, consideration is given to taking into account heat transfers from the thermopile, that the emissivity ε_c may not be unity, and that the dome is not completely opaque to the solar irradiance. The model of the pyrgeometer is shown in Figure 1.

It is assumed that the IR irradiance, the temperatures T_d, T_c, T_s are stable (in normal use of the pyrgeometer these quantities may vary slowly).

The net radiation on the receiver surface may be written as:

$$R_{net} = R_{in} - R_{out} \qquad (1)$$

where

$$R_{in} = \underbrace{A(\downarrow)\tau(\downarrow) + Gt_g}_{(a)} + \underbrace{\rho(\uparrow)R(\uparrow)_{out}}_{(b)} + \underbrace{\varepsilon(\uparrow)\sigma T_d^4}_{(c)} \qquad (2)$$

$$R_{out} = \underbrace{\varepsilon_c \sigma T_s^4}_{(d)} + \underbrace{\rho_c R_{in}}_{(e)} + \underbrace{B(T_s - T_c)}_{(f)} + \underbrace{C(T_s - T_D)}_{(g)} \qquad (3)$$

The contributing terms in equations (2) and (3) are as follows:

(a) represents the power of IR and spectral global irradiance transmitted through the dome to the thermopile surface,

(b) represents the part of the power emitted from the sensor surface and reflected back to the sensor by the inside of the dome,

(c) represents the power emitted from the dome to the sensor,

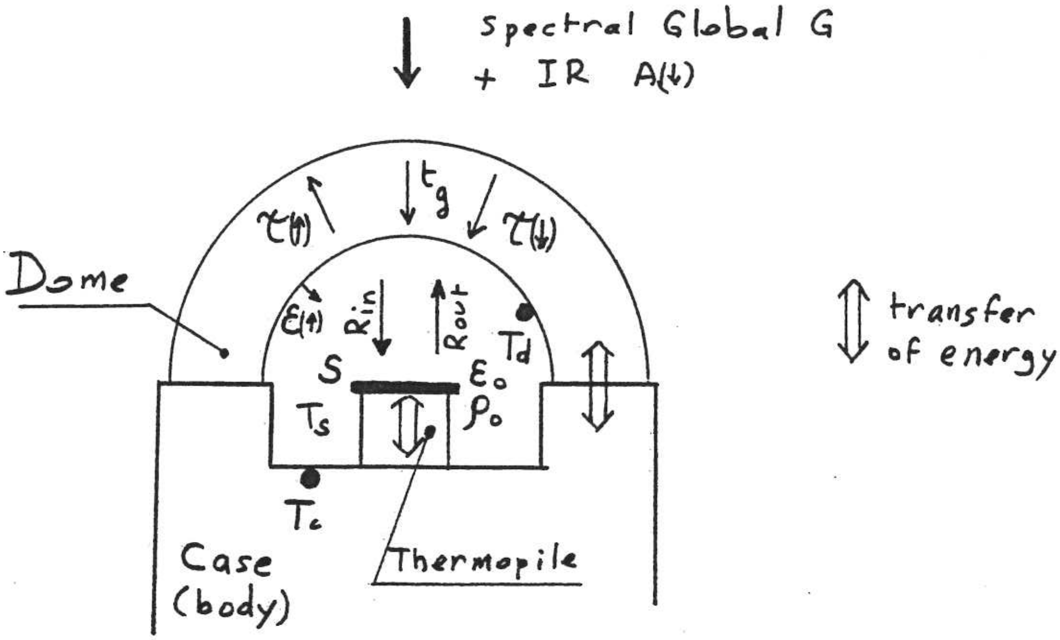


Figure 1. Pyrgeometer Model

List of symbols:

$A(\downarrow)$	: atmospheric IR irradiance (W/m^2)	ε_o	: emissivity of the thermopile surface
G	: spectral global irradiance (W/m^2)	ρ_o	: reflectivity of the thermopile surface
$\tau(\uparrow)$	: transmissivity: ratio of the IR irradiance transmitted through the dome to that incident upon the inside surface of the dome	T_s	: thermopile surface temperature
		T_d	: dome temperature
$\tau(\downarrow)$	: transmissivity: ratio of the IR irradiance transmitted through the dome to that incident upon the outside surface of the dome	T_c	: case (or body) temperature
		B	: heat transfer coefficient between thermopile surface and case ($W/m^2/K$)
t_g	: transmissivity of the dome for global irradiance	C	: heat transfer coefficient between thermopile surface and dome ($W/m^2/K$)
$\rho(\uparrow)$	: reflectivity of the inside of the dome	V_{AC}	: thermopile output
$\varepsilon(\uparrow)$	: emissivity of the inside of the dome	σ	: Stefan-Boltzmann constant (5.67×10^{-8} $W/m^2/K^4$)

(d) represents the loss of power by emission from the thermopile surface,

(e) represents the part of the R_{in} irradiance reflected by the thermopile surface,

(f) represents the transfer of power between the thermopile surface and the case (body) of the pyrgeometer,

(g) represents the transfer of power between the thermopile surface and the dome of the pyrgeometer.

In the term (b), $R(\uparrow)_{out}$ is the power emitted by thermopile surface, and can be expressed as:

$$R(\uparrow)_{out} = \varepsilon_o \sigma T_s^4 + \rho R_{in} \tag{4}$$

(2) and (4) give:

$$R_{in} = \frac{A(\downarrow)\tau(\downarrow) + G t_g + \rho(\uparrow)\varepsilon_o \sigma T_s^4 + \varepsilon(\uparrow)\sigma T_d^4}{1-\rho(\uparrow)\rho_o} = \frac{P}{Q} \tag{5}$$

Eq. (1) may be written as:

$$R_{net} = \frac{P}{Q} - \rho_o \frac{P}{Q} - \varepsilon_o \sigma T_s^4 - B(T_s - T_c) - C(T_s - T_d) \tag{6}$$

Rearranging the two first terms of (6) and noting that

$$(1-\rho_o) = \varepsilon_o$$

$$R_{net} = \varepsilon_o \frac{P}{Q} - \varepsilon_o \sigma T_s^4 - B(T_s - T_c) - C(T_s - T_d) \tag{7}$$

$$P = \frac{Q R_{net}}{\varepsilon_o} + Q\sigma T_s^4 + \frac{BQ}{\varepsilon_o}(T_s - T_c) - \frac{CQ}{\varepsilon_o}(T_s - T_d) \tag{8}$$

Using (5):

$$A(\downarrow)\tau(\downarrow) + G t_g + \rho(\uparrow)\varepsilon_o \sigma T_s^4 + \varepsilon(\uparrow)\sigma T_d^4$$
$$= \frac{Q R_{net}}{\varepsilon_o} + (1-\rho(\uparrow)\rho_o)\sigma T_s^4 + \frac{BQ}{\varepsilon_o}(T_s - T_c) + \frac{CQ}{\varepsilon_o}(T_s - T_d) \tag{9}$$

Expanding the second term on the righthand side of (9):

$$A(\downarrow)\tau(\downarrow) = \frac{Q R_{net}}{\varepsilon_o} + \sigma T_s^4 - \rho(\uparrow)\rho_o \sigma T_s^4 - \rho(\uparrow)\varepsilon_o \sigma T_s^4$$
$$- \varepsilon(\uparrow)\sigma T_d^4 - G t_g + \frac{BQ}{\varepsilon_o}(T_s - T_c) + \frac{CQ}{\varepsilon_o}(T_s - T_d) \tag{10}$$

Adding and subtracting $\varepsilon(\uparrow)\sigma T_s^4$ from the righthand side of (10)

$$A(\downarrow)\tau(\downarrow) = \frac{Q R_{net}}{\varepsilon_o} + \sigma T_s^4 (1 - \rho(\uparrow)\rho_o - \rho(\uparrow)\varepsilon_o - \varepsilon(\uparrow))$$
$$- \varepsilon(\uparrow)\sigma (T_d^4 - T_s^4) - G t_g + \frac{BQ}{\varepsilon_o}(T_s - T_c) + \frac{CQ}{\varepsilon_o}(T_s - T_d) \tag{11}$$

The second term on the righthand side of (11) may be written as:

$$(1 - \rho(\uparrow)\rho_o - \rho(\uparrow)\varepsilon_o - \varepsilon(\uparrow) = 1 - \rho(\uparrow)(\rho_o + \varepsilon_o) - \varepsilon(\uparrow)$$
$$= 1 - \rho(\uparrow) - \varepsilon(\uparrow)$$
$$= \tau(\uparrow)$$

(11) thus becomes:

$$A(\downarrow)\tau(\downarrow) = \frac{QR_{net}}{\varepsilon_o} + \tau(\uparrow)\sigma T_s^4 - \varepsilon(\uparrow)\sigma(T_d^4 - T_s^4) - Gt_g + \frac{BQ}{\varepsilon_o}(T_s - T_c) + \frac{CQ}{\varepsilon_o}(T_s - T_d) \tag{12}$$

The temperature of the thermopile surface may be expressed as:

$T_s = T_c + \Delta T$ or $\Delta T = T_s - T_c$

with $T \ll T_c$

Since $T \ll T_c$:

$$T_s^4 \simeq T_c^4 + 4T_c^3\Delta T$$

(12) may then be written as:

$$A(\downarrow) = \frac{QR_{net}}{\varepsilon_o} + \tau(\uparrow)\sigma(T_c^4 + 4T_c^3\Delta T) - \varepsilon(\uparrow)\sigma(T_d^4 - T_c^4 - 4T_c^3\Delta T) - Gt_g + \frac{BQ}{\varepsilon_o}\Delta T + \frac{CQ}{\varepsilon_o}(T_c + \Delta T - T_d) \tag{13}$$

Since T is proportional to R_{net}:

$$T = m.R_{net}$$

Substituting in (13):

$$A(\downarrow)\tau(\downarrow) = R_{net}\left[\frac{Q}{\varepsilon_o} + \frac{m}{\varepsilon_o}(BQ + CQ) + 4m\sigma(\tau(\uparrow) - \varepsilon(\uparrow)T_c^3\right] + \tau(\uparrow)\sigma T_c^4 - \varepsilon(\uparrow)\sigma(T_d^4 - T_c^4) - \frac{CQ}{\varepsilon_o}(T_d - T_c) - Gt_g \tag{14}$$

The output signal of the thermopile is proprotional to R_{net} and thus the atmospheric IR irradiance A( ) may be written as:

$$A(\downarrow) = V_{Ac}(C_1 + C_2T_c^3) + \frac{\tau(\uparrow)}{\tau(\downarrow)}\sigma T_c^4 - \frac{\varepsilon(\uparrow)}{\tau(\downarrow)}\sigma(T_d^4 - T_c^4) - \frac{C_3}{\tau(\downarrow)}(T_d - T_c) - \frac{t_g}{\tau(\downarrow)}G \tag{15}$$

where C_1, C_2, C_3 are constants

It is noted that $(C_1 + C_2 T_c^3) = \mu$, (15) is almost the same as the formulation used by the Atmospheric Environment Service, Canada. However, in the present study, the second term on the righthand side of (15) is retained, even though the factor $\frac{\tau(\uparrow)}{\tau(\downarrow)}$ is close to unity (see discussion in Annex 4).

2. Inventory of Errors

(15) is considered as the reference formula. Before considering errors that can occur, (0) shows that for IR radiation measurements:

$$L(\downarrow) = \frac{E}{\eta} + \varepsilon_o\sigma T_c^4 - k\sigma(T_d^4 - T_c^4)$$

or:

$$A(\downarrow) = V_{Ac}/k + \sigma T_c^4 - k\sigma(T_d^4 - T_c^4) \tag{0}$$

where $k \simeq 4$ (Cf. (15)).

In Carpentras, a shading disk is used so, in cloudless sky conditions, it may be assumed that the pyrgeometer is opaque to the diffuse radiation.

(15) then becomes:

$$A(\downarrow) = \frac{V_{AC}}{k} + \frac{\tau(\uparrow)}{\tau(\downarrow)}\sigma T_c^4 - \frac{\varepsilon(\uparrow)}{\tau(\downarrow)}\sigma(T_d^4 - T_c^4) - \frac{C_3}{\tau(\downarrow)}(T_d - T_c)$$

or in simplified form:

$$A(\downarrow) = \frac{V_{AC}}{k} + \sigma T_c^4 - Q_1\sigma(T_d^4 - T_c^4) - Q_2(T_d - T_c) \tag{16}$$

Now $(T_d^4 - T_c^4) = (T_d - T_c)(T_d + T_c)(T_d^2 + T_c^2)$. Assuming $T_d \simeq T_c$, this may be written as:

$$(T_d^4 - T_c^4) \simeq 4T_c^3 (T_d - T_c)$$

Substituting in (16):

$$A(\downarrow) = \frac{V_{AC}}{k} + \sigma T_c^4 - Q_1\sigma 4T_c^3(T_d - T_c) - Q_2(T_d - T_c) \tag{17}$$

Taking $4\sigma T_c^3 (T_d - T_c)$ from the third and fourth terms on the righthand side of (17):

$$A(\downarrow) = \frac{V_{AC}}{k} + \sigma T_c^4 - 4\sigma T_c^3 (T_d - T_c)\left(Q_1 + \frac{Q_2}{4\sigma T_c^3}\right) \tag{18}$$

$$\text{where } k = \left(Q_1 + \frac{Q_2}{4\sigma T_c^3}\right) \tag{19}$$

Using the approximation $(T_d^4 - T_c^4) \simeq 4T_c^3 (T_d - T_c)$, (19) may be written as:

$$A(\downarrow) = \frac{V_{AC}}{k} + \sigma T_c^4 - k\sigma (T_d^4 - T_c^4) \tag{20}$$

In (20), k <u>is not</u> the same coefficient as in (15); $k \simeq 4$ is a good value for the measurements made in Carpentras using (0) or (20).

The last term on the righthand side of (15) $t_3 C_3/\tau(\downarrow)$, may be neglected in cloudless conditions if a shading disk is used, otherwise the effects of shortwave radiation should be added to the effects of the temperature elevation of the dome (see Annex 4). With a shading disk, it is possible to determine experimentally the (slowly varying) values of "k" (see Figure 2).

Note that, using (19), "k" can be "calculated" for a given temperature T_c, but since the coefficients Q_1 and Q_2 (also $\rho(\uparrow)$, heat transfer coefficient, C) are only roughly known, the result of the calculation is not very accurate (e.g., for T_c = 288K, "k" $\simeq$ 9; (twice the "normal" value, but not an order of magnitude more or less).

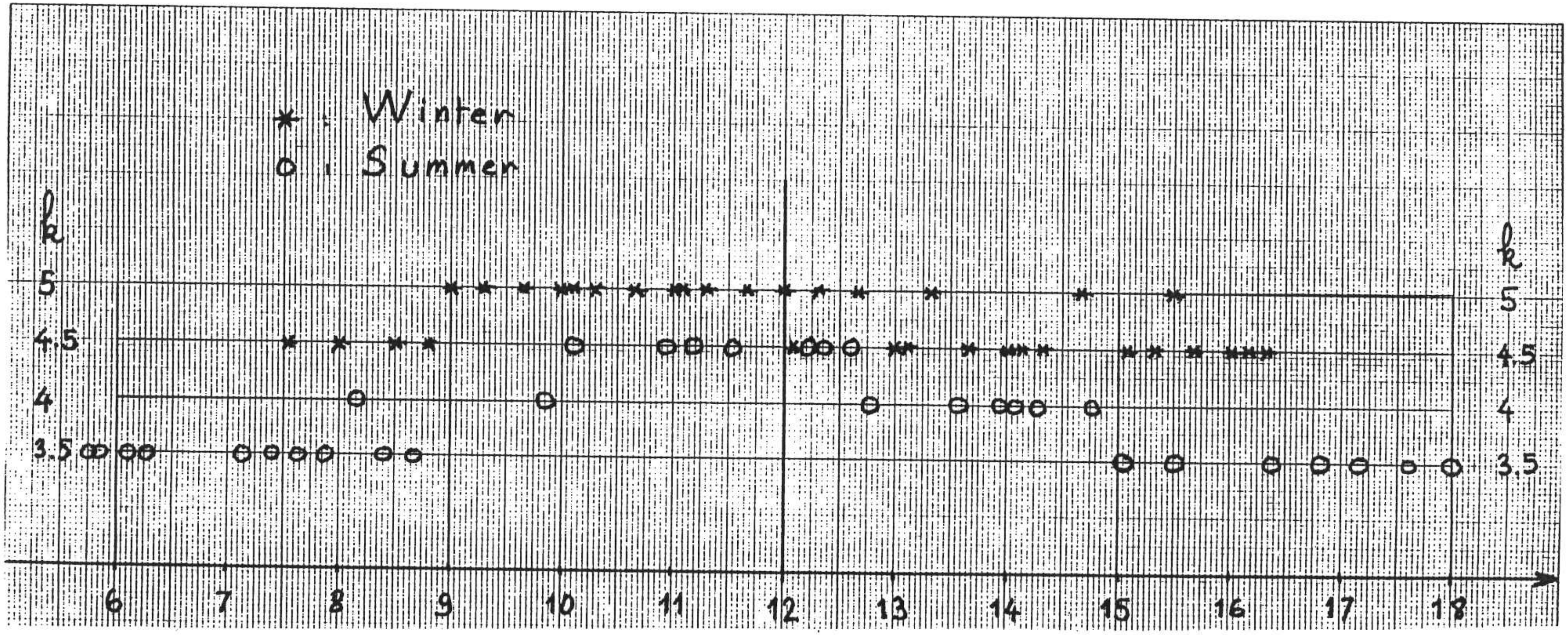


Figure 2. Best values of k giving the ratio of result measurement irradiances - with or without a shading disk - close to unity: "k" is taken as: 3.5; 4; 4.5; 5.

Pyrgeometer measurement errors

Errors are classified in three categories:

(1): relating to the outside of the pyrgeometer and the installation (A) and the automatic compensation of the detected flux, automatically compensated by the manufacturer (B).

	Error type	Remarks and remedy for error reduction	Error estimation
A	Dust on the dome	Clean the dome at least once a day	variable
A	Liquid or solid water deposits on the dome	Use ventilation system, clean the dome	variable
A	Deviation from the ideal cosine law		insignificant
A	Obstruction from free horizon Shading disk	See WMO recommendations See Annex 1	variable
B	Calibration		5%?
B	Compensation circuit	See Annex 2	0 to 10W/m^2
B	Dome temperature	Eppley assumes $T_d \simeq T_c$ but $(T_d - T_c)$ can reach 1°C, sometimes more, use a shading disk See Annex 3	0 to 20W/m^2

(2) relating the errors in "reference" equation (15). Expressing (15) in the form,

$$A(\downarrow) = V_{Ac}\left(C_1+C_2T_c^3\right)+\frac{\tau(\uparrow)}{\tau(\downarrow)}\sigma T_c^4-\frac{\varepsilon(\uparrow)}{\tau(\downarrow)}\sigma\left(T_d^4-T_c^4\right)-\frac{C_3}{\tau(\downarrow)}\left(T_d-T_c\right)-\frac{t_g G}{\tau(\downarrow)}$$

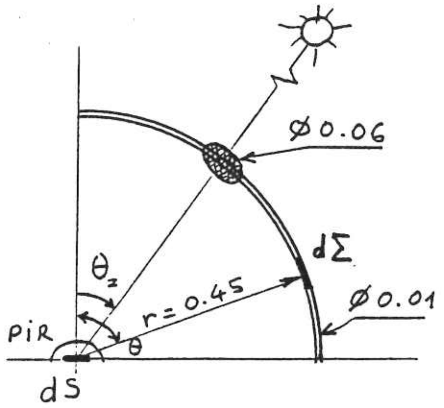
the contribution of each term to overall errors is indicated below.

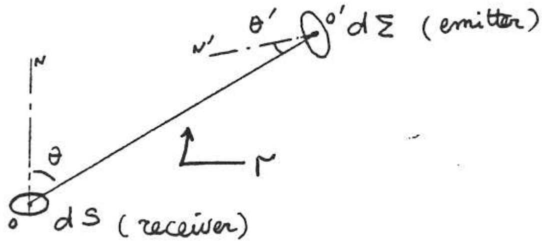
		Remarks and remedy for error reduction	Error estimation
	<u>First term</u>		
1	V_{AC}	V_{AC} varies from 0 to -500 μm; use a preamplificator with electric filter	$\pm$ 10 μm or $\pm$ 2W/m^2
2	$(C_1 + C_2T_c) = \frac{1}{K}$	K: constant for the instrument, calibration not easy	3 to 5% or 3 to 5W/m^2
	<u>Second term</u>		
3	$\frac{\tau(\uparrow)}{\tau(\downarrow)}$	Value approximately 1, see Annex 4	1% or 4W/m^2
4	T_c	Error 0.2K	1W/m^2
	<u>Third, fourth and fifth terms</u>	These may be considered as corrective terms. The sum of terms 3 and 4 can be written as k $(T_d - T_c)$	
5	k	k $\simeq$ 4	25%; $\sim$5W/m^2
6	$(T_d^4 - T_c^4)$	T_d is the temperature measured at a single point of the dome rim; (error 0.2 to 0.5K?), use a shading disk	4 to 8W/m^2
7	$\frac{t_g G}{\tau(\downarrow)}$	G: spectral global irradiance values: summer: 2.5 to 3W/m^2 winter: 1 to 2W/m^2 See Annex 4, use a shading disk	1 to 2 W/m^2 insignificant

(3): relating to the data acquisition system.

	Error type	Remarks and remedy	Error estimation
1	Voltage measurement	Data logger Heliss I, use preamplification and an electric filter	$\pm$ 10μV $1Wm^{-2}$
2	Thermistor measurement	"Standard" thermistor	$\pm$ 0.1K
3	Time	Correction if the drift is more than one minute	

Error due to the shading disk and its support





The radiant flux density on dS is given by the formula:

$$E = \frac{L \, d\Sigma \cos\theta \cos\theta'}{r^2} \tag{1}$$

where L is the radiance (of $d\Sigma$) $= \frac{\sigma T}{\pi}$

For the pyrgeometer:

$$E_m = \frac{L_m S_d \cos\theta_2}{r^2} + \frac{L_m \, d\Sigma \cos\theta}{r^2} \tag{2}$$

where: L_m is masking effect (disk + support) radiance; S_d is the surface of the disk ($0.0028 m^2$), θ_2 is the zenith angle; $d\Sigma$ an element of the surface of the support.

Integrating (2):

$$E_m = \frac{L_m}{r^2}\left(0.0028 \cos\theta_2 + 0.0045\right) \tag{3}$$

The part of the radiant flux density from the sky that is hidden by masking may be written as:

$$E_s = \frac{L_s}{r^2}\left(0.0028 \cos\theta_2 + 0.0045\right) \tag{4}$$

where L_s is the sky radiance.

Assuming the disk and support emit as a black body: $L_m = \sigma T_M^4 / \pi$; $L_s = \sigma T_s^4 / \pi$
(T_m is the temperature of the mask, T_s is the apparent temperature of the sky)

The error may then be written as:

$$E_m - E_s = \frac{\sigma}{\pi}\left(\frac{0.0028 \cos\theta_2 + 0.0045}{r^2}\right)\left(T_M^4 - T_s^4\right) \tag{5}$$

Examples of calculation of errors (upper limits at noon)

Summer: Irradiance = 400 Wm^{-2}, T_s = 290K
T_m = 308K (~35°C) and θ_2 = 22°: error = 1.22 Wm^{-2}

Winter: Irradiance = 220 Wm^{-2}, T_s = 248K
T_m = 278K and $_2$ = 68°: error = 1.05 Wm^{-2}

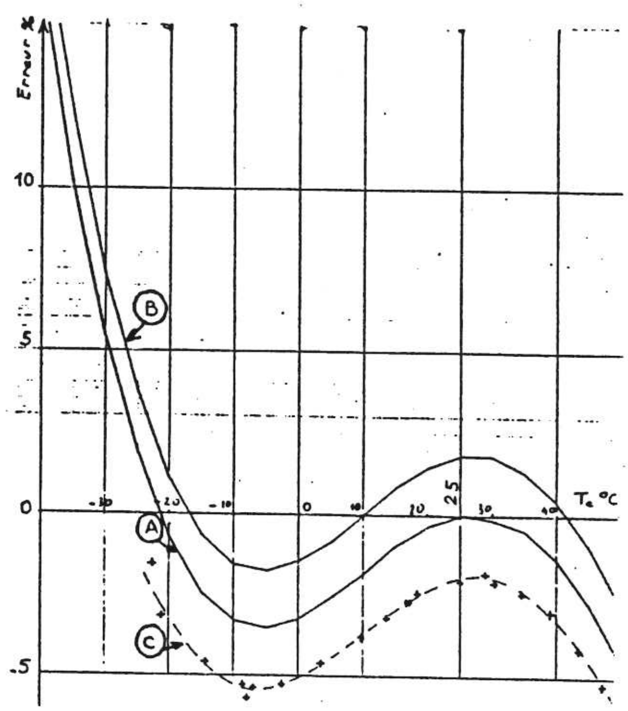
Compensation circuit errors

The figure below depicts the error (%) generated by the internal compensation circuit, calculated theoretically.

A : the function σT_c^4 is correctly simulated for T_c = + 25°C

B : the function σT_c^4 is correctly simulated for T_c = + 10°C

C : experimental points: the variable resistor used to match thermopile sensitivity is certainly out of adjustment (battery voltage was correct during the test).



Overheating of pyrgeometer dome

Overheating of the pyrgeometer dome depends on whether or not a shading disk is used. Figure 2 shows the overheating of the dome during hot days in July at Carpentras (temperatures reached 37°C). Nonetheless, using equation (20), measurements from the IR irradiance pyrgeometer were very close.

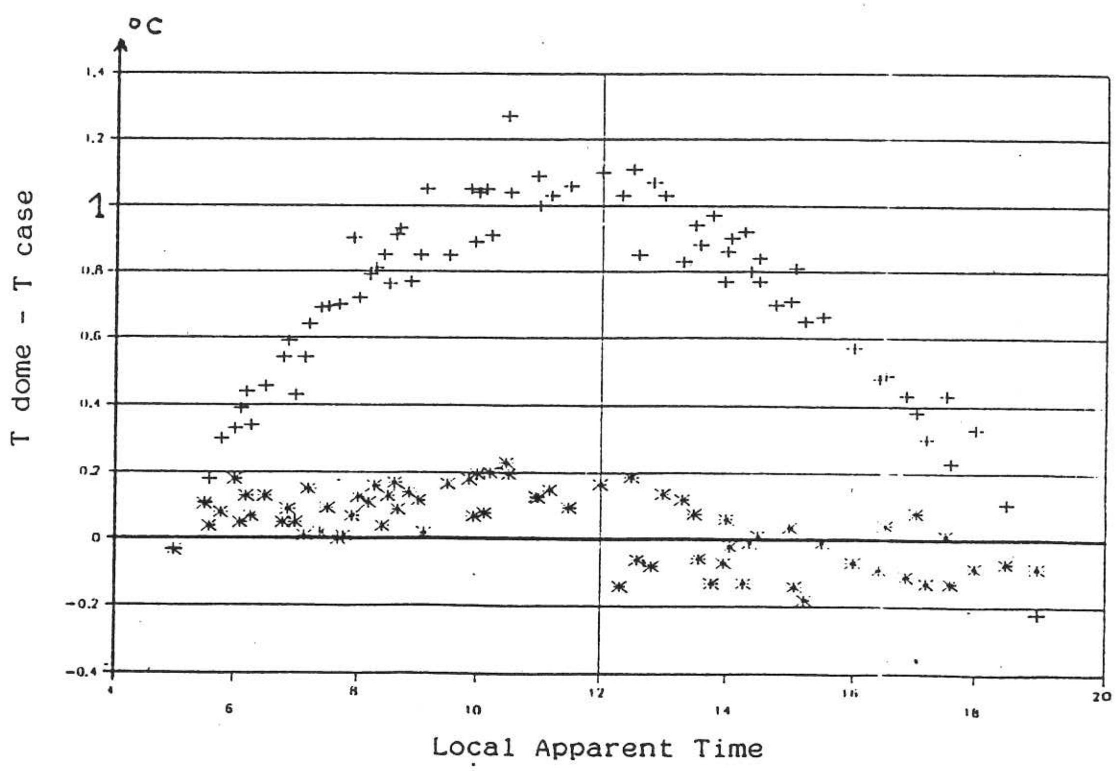


Figure 2: Overheating of the pyrgeometer dome:
* tracking disk used
\+ tracking disk not used.

Transmissivity of a silicon dome ($\tau(\uparrow), \tau(\downarrow)$, tg)

Transmissivity is defined as the ratio of the irradiance transmitted through the dome to that incident upon the surface of the dome on the opposite side. For long-wave radiation:

$$\tau(\uparrow) = \frac{\int_{\lambda=2.5}^{100} I_{1\lambda} T_\lambda \, d\lambda}{\int_{\lambda=2.5}^{100} I_{1\lambda} \, d\lambda} \quad \text{and} \quad \tau(\downarrow) = \frac{\int_{\lambda=2.5}^{100} I_{2\lambda} T_\lambda \, d\lambda}{\int_{\lambda=2.5}^{100} I_{2\lambda} \, d\lambda} \qquad (1,2)$$

where:

$I_{1\lambda}$ represents the IR spectral irradiance from the thermopile surface as a grey body (ε_o is unimportant),

$I_{2\lambda}$ represents the IR spectral irradiance from the atmosphere. Plots of $I_{2\lambda}$ for typical midlatitude meteorological conditions during the summer and the winter are shown in Figure 1.

T_λ represents the spectral transmission of a silicon pyrgeometer dome, (T_λ is approximately known, as also shown in Figure 1).

Computed values using (1) and (2) are shown in Table 1.

	$\tau(\uparrow)$	$\tau(\downarrow)$	$\tau(\uparrow)/\tau(\downarrow)$
Summer	0.3469	0.3443	1.0076
Winter	0.3428	0.3398	1.0088
mean	0.3449	0.3421	1.0082

Table 1. IR transmissivities of a silicon dome

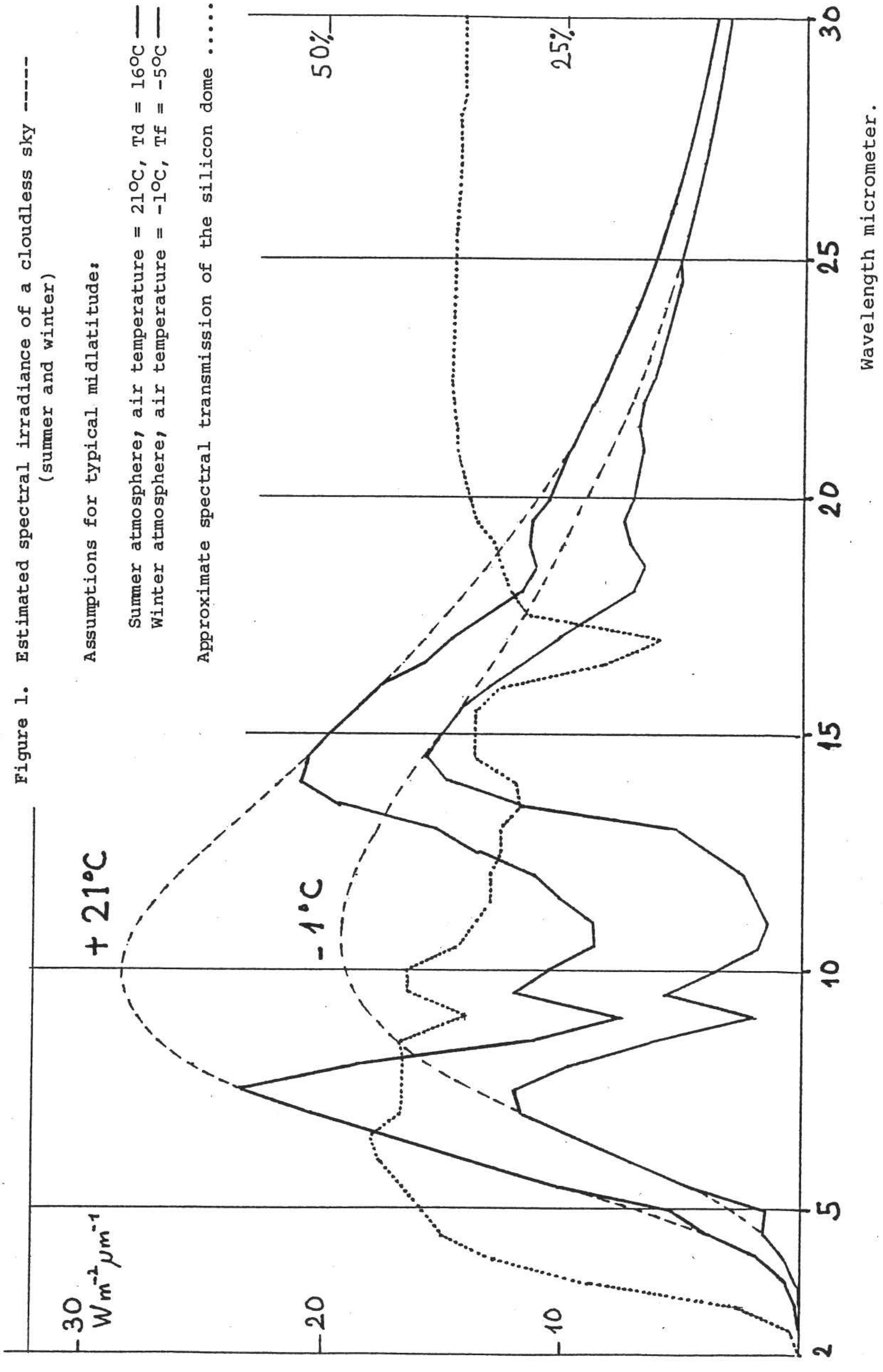


Figure 1. Estimated spectral irradiance of a cloudless sky ------
(summer and winter)

Assumptions for typical midlatitude:

Summer atmosphere, air temperature = 21°C, Td = 16°C ——
Winter atmosphere, air temperature = -1°C, Tf = -5°C ——

Approximate spectral transmission of the silicon dome ......

Transmissivity of the silicon dome for the short-wave radiation

It is assumed that global irradiance is negligible beyond 5μm. For the global irradiance in the spectral interval 2.5 - 5μm:

$$[G]_{\lambda=2.5}^{5} = [I_n]_{2.5}^{5} \cos \theta_z + [\text{Diffuse}]_{2.5}^{5} \tag{3}$$

where:

$[I_n]$ is the direct normal spectral interval solar irradiance

θ_z is the zenith angle

(It is assumed that the diffuse irradiance is negligible (cloudless skies)

$$[I_n]_{2.5}^{5} = \int_{\lambda=2.5}^{5} I_{on\lambda}\, S\, T_{r\lambda}\, T_{a\lambda}\, T_{w\lambda}\, T_{g\lambda}\, d\lambda \tag{4}$$

where:

$I_{on\lambda}$ is the extraterrestrial solar spectral irradiance at the mean Sun-Earth Distance,

S is the inverse of the eccentricity correction factor of the earth's orbit ($S = 1/E_o$),

$T_{r\lambda}$, $T_{a\lambda}$, $T_{w\lambda}$, $T_{g\lambda}$ are respectively the spectral transmittance of the atmosphere due to Rayleigh scattering, aerosol scattering, water-vapor absorption, mixed gases absorption.

The part of $[I_n]_{2.5}^{5}$ transmitted by the dome may be written as:

$$[I_{tn}]_{\lambda=2.5}^{5} = \int_{\lambda=2.5}^{5} (I_{on\lambda}\, S\, T_{r\lambda}\, T_{a\lambda}\, T_{w\lambda}\, T_{g\lambda})\, \tau_\lambda\, d\lambda \tag{5}$$

where:

τ_λ is the spectral transmission of the dome.

The part of $[G]_{2.5}^{5}$ transmitted by the dome may be written as:

$$[G_t]_{2.5}^{5} = [I_{tn}]_{2.5}^{5} \cos \theta_z \tag{6}$$

(diffuse is neglected)

Solving Eqs. (3) to (6) in the meteorological conditions shown in Table 2, it is possible to estimate the value of the fifth term of (15): $t_3 G/\tau(\downarrow)$. In the summer, the approximate value at noon is 0.71 x 3.69 = 2.6 Wm^{-2}, in winter, the approximate value at noon is 0.67 x 1.49 = 1.0 Wm^{-2}. The diffuse radiation is certainly less than 10% of these values in cloudless conditions.

TABLE 2

Transmisssivity of a silicon dome for short-wave radiation at noon for typical meteorological conditions for summer and winter midlatitude sites.

	Summer	Winter	Remark
Time	12:00	12:00	Local time
Air mass	1.08	2.67	$\sim 1/\cos\theta_z$
θ_z	22°	68°	Zenith angle
w	3	0.7	precipitable water (gcm^{-2})
β Angström	0.050	0.025	Turbidity (not very important)
S	1.034	0.967	Earth-Sun distance correction
$[I_n]_{\lambda=2.5}^{5}$	3.9778	3.9903	Wm^{-2}
$[G]_{\lambda=2.5}^{5}$	3.6882	1.4948	With cloudless skies diffuse is neglected
$[I_{ta}]_{\lambda=2.5}^{5}$	0.9768	0.9020	Wm^{-2}
$[G_t]_{\lambda=2.5}^{5}$	0.9056	0.3379	Wm^{-2}
t_g	0.2456	0.2261	$t_g = \frac{[G_t]_{2.5}^{5}}{[G]_{2.5}^{5}}$
$t_g/\tau(\downarrow)$	0.7132	0.6653	

LIST OF REPORTS

WCRP-1	VALIDATION OF SATELLITE PRECIPITATION MEASUREMENTS FOR THE GLOBAL PRECIPITATION CLIMATOLOGY PROJECT (Report of an International Workshop, Washington, D.C., 17-21 November 1986) (WMO/TD-No. 203)
WCRP-2	WOCE CORE PROJECT 1 PLANNING MEETING ON THE GLOBAL DESCRIPTION (Washington, D.C., USA, 10-14 November 1986) (WMO/TD-No. 205)
WCRP-3	INTERNATIONAL SATELLITE CLOUD CLIMATOLOGY PROJECT (ISCCP) WORKING GROUP ON DATA MANAGEMENT (Report of the Sixth Session, Fort Collins, USA, 16-18 June 1987) (WMO/TD-No. 210)
WCRP-4	JSC/CCCO TOGA NUMERICAL EXPERIMENTATION GROUP (Report of the First Session, Unesco, Paris, France, 25-26 June 1987) (WMO/TD No. 204)
WCRP-5	CONCEPT OF THE GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (Report of the JSC Study Group on GEWEX, Montreal, Canada, 8-12 June 1987 and Pasadena, USA, 5-9 January 1988) (WMO/TD-No. 215) (out of print)
WCRP-6	INTERNATIONAL WORKING GROUP ON DATA MANAGEMENT FOR THE GLOBAL PRECIPITATION CLIMATOLOGY PROJECT, (Report of the Second Session, Madison, USA, 9-11 September 1988) (WMO/TD-No. 221) (out of print)
WCRP-7	CAS GROUP OF RAPPORTEURS ON CLIMATE, (Leningrad, USSR, 28 October-1 November 1985) (WMO/TD-No. 226)
WCRP-8	JSC WORKING GROUP ON LAND SURFACE PROCESSES AND CLIMATE, (Report of the Third Session, Manhattan, USA, 29 June-3 July 1987) (WMO/TD-No. 232)
WCRP-9	AEROSOLS, CLOUDS AND OTHER CLIMATICALLY IMPORTANT PARAMETERS: LIDAR APPLICATIONS AND NETWORKS, (Report of a Meeting of Experts, Geneva, Switzerland, 10-12 December 1985) (WMO/TD-No. 233)
WCRP-10	RADIATION AND CLIMATE: (Report of the First Session, JSC Working Group on Radiative Fluxes, Greenbelt, USA, 14-17 December 1987) (WMO/TD-No. 235)
WCRP-11	WORLD OCEAN CIRCULATION EXPERIMENT - IMPLEMENTATION PLAN - DETAILED REQUIREMENTS (Volume I) (WMO/TD-No. 242)
WCRP-12	WORLD OCEAN CIRCULATION EXPERIMENT - IMPLEMENTATION PLAN - SCIENTIFIC BACKGROUND (Volume II) (WMO/TD-No. 243)
WCRP-13	RADIATION AND CLIMATE (Report of the Seventh Session of the International Satellite Cloud Climatology Project (ISCCP) Working Group on Data Management, Banff, Canada, 6-8 July 1988) (WMO/TD-No. 252)
WCRP-14	AN EXPERIMENTAL CLOUD LIDAR PILOT STUDY (ECLIPS) (Report of the WCRP/CSIRO Workshop on Cloud Base Measurement, CSIRO, Mordialloc, Victoria, Australia, 29 February-3 March 1988) (WMO/TD-No. 251)
WCRP-15	MODELLING THE SENSITIVITY AND VARIATIONS OF THE OCEAN-ATMOSPHERE SYSTEM (Report of a Workshop at the European Centre for Medium Range Weather Forecasts, 11-13 May 1988) (WMO/TD-No. 254)

WCRP-16 GLOBAL DATA ASSIMILATION PROGRAMME FOR AIR-SEA FLUXES (Report of the JSC/CCCO Working Group on Air-Sea Fluxes, October 1988) (WMO/TD-No. 257)

WCRP-17 JSC/CCCO TOGA SCIENTIFIC STEERING GROUP (Report of the Seventh Session, Cairns, Queensland, Australia, 11-15 July 1988) (WMO/TD-No. 259)

WCRP-18 SEA ICE AND CLIMATE (Report of the Third Session of the Working Group on Sea Ice and Climate, Oslo, 31 May-3 June 1988) (WMO/TD-No. 272)

WCRP-19 THE GLOBAL PRECIPITATION CLIMATOLOGY PROJECT (Report of the Third Session of the International Working Group on Data Management, Darmstadt, FRG, 13-15 July 1988) (WMO/TD-No. 274)

WCRP-20 RADIATION AND CLIMATE (Report of the Second Session of the WCRP Working Group on Radiative Fluxes, Geneva, Switzerland, 19-21 October 1988) (WMO/TD No. 291)

WCRP-21 INTERNATIONAL WOCE SCIENTIFIC CONFERENCE (Report of the International WOCE Scientific Conference, Unesco, Paris, 28 November to 2 December 1988) (WMO/TD No. 295)

WCRP-22 THE GLOBAL WATER RUNOFF DATA PROJECT (Workshop on the Global Runoff Data Set and Grid estimation, Koblenz, FRG, 10-15 November 1988) (WMO/TD No. 302)

WCRP-23 WOCE SURFACE FLUX DETERMINATIONS - A STRATEGY FOR IN SITU MEASUREMENTS (Report of the Working Group on In Situ Measurements for Fluxes, La Jolla, California, USA, 27 February-3 March 1989) (WMO/TD No. 304)

WCRP-24 JSC/CCCO TOGA NUMERICAL EXPERIMENTATION GROUP (Report of the Second Session, Royal Society, London, UK, 15-16 December 1988) (WMO/TD-No. 307)

WCRP-25 GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (GEWEX) (Report of the First Session of the JSC Scientific Steering Group for GEWEX, Pasadena, USA, 7-10 February 1989) (WMO/TD-No. 321) (out of print)

WCRP-26 WOCE GLOBAL SURFACE VELOCITY PROGRAMME (SVP) (Workshop Report of WOCE/SVP Planning Committee and TOGA Pan-Pacific Surface Current Study, Miami, Florida, USA, 25-26 April 1988) (WMO/TD-No. 323)

WCRP-27 DIAGNOSTICS OF THE GLOBAL ATMOSPHERIC CIRCULATION (Based on ECMWF analyses 1979-1989, Department of Meteorology, University of Reading, Compiled as part of the U.K. Universities Global Atmospheric Modelling Project) (WMO/TD-No. 326)

WCRP-28 INVERSION OF OCEAN GENERAL CIRCULATION MODELS (Report of the CCCO/WOCE Workshop, London, 10-12 July 1989) (WMO/TD-No. 331)

WCRP-29 CAS WORKING GROUP ON CLIMATE RESEARCH (Report of Session, Geneva, 22-26 May 1989) (WMO/TD-No. 333)

WCRP-30 WOCE - FLOW STATISTICS FROM LONG-TERM CURRENT METER MOORINGS: THE GLOBAL DATA SET IN JANUARY 1989 (Report prepared by Robert R. Dickinson, Eddy Statistics Scientific Panel) (WMO/TD-No. 337)

WCRP-31 JSC/CCCO TOGA SCIENTIFIC STEERING GROUP (Report of the Eighth Session, Hamburg, FRG, 18-22 September 1989) (WMO/TD-No. 338)

WCRP-32 JSC/CCCO TOGA NUMERICAL EXPERIMENTATION GROUP (Report of the Third Session, Hamburg, FRG, 18-20 September 1989) (WMO/TD-No. 339)

WCRP-33 TOGA MONSOON CLIMATE RESEARCH (Report of the First Session of the Monsoon Numerical Experimentation Group, Hamburg, FRG, 21-22 September 1989) (WMO/TD-No. 349)

WCRP-34 THE GLOBAL PRECIPITATION CLIMATOLOGY PROJECT (Report of the Fourth Session of the International Working Group on Data Management, Bristol, UK, 26-28 July 1989) (WMO/TD-No. 356)

WCRP-35 RADIATION AND CLIMATE (Report of the Third Session of the WCRP Working Group on Radiative Fluxes, Fort Lauderdale, USA, 12-15 December 1989) (WMO/TD-No. 364)

WCRP-36 LAND-SURFACE PHYSICAL AND BIOLOGICAL PROCESSES (Report of an ad-hoc Joint Meeting of the IGBP Co-ordinating Panel No.3 and WCRP Experts, Paris, France, 24-26 October 1989) (WMO/TD-No. 368)

WCRP-37 GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (Report of the Workshop to Evaluate the Need for a Rain Radar in Polar Orbit for GEWEX, Greenbelt, USA, 25-26 October 1989) (WMO/TD-No. 369)

WCRP-38 GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (Report of the First Session of the WCRP-GEWEX/IGBP-CP3 Joint Working Group on Land-Surface Experiments, Wallingford, UK, 25-26 January 1990) (WMO/TD No. 370)

WCRP-39 RADIATION AND CLIMATE (Intercomparison of Radiation Codes in Climate Models, Report of Workshop, Paris, France, 15-17 August 1988) (WMO/TD No. 371)

WCRP-40 GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (Scientific Plan), August 1990 (WMO/TD-No. 376)

WCRP-41 SEA-ICE AND CLIMATE (Report of the fourth session of the Working Group, Rome, Italy, 20-23 November, 1989) (WMO/TD-No. 377)

WCRP-42 PLANETARY BOUNDARY LAYER (Model Evaluation Workshop, Reading, U.K., 14-15 August 1989) (WMO/TD-No. 378)

WCRP-43	INTERNATIONAL TOGA SCIENTIFIC CONFERENCE PROCEEDINGS (Honolulu, USA, 16-20 July 1990) (WMO/TD-No. 379)
WCRP-44	GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (Report of the 2nd Session of the JSC Scientific Steering Group, Paris, France, 15-19 January 1990) (WMO/TD-No. 383)
WCRP-45	SEA ICE NUMERICAL EXPERIMENTATION GROUP (SINEG) (Report of the First Session, Washington, D.C., 23-25 May 1989) (WMO/TD-No. 384)
WCRP-46	EARTH OBSERVING SYSTEM FOR CLIMATE RESEARCH (Report of a WCRP Planning Meeting, Reading, U.K., 2-3 July 1990) (WMO/TD-No. 388)
WCRP-47	JSC/CCCO TOGA SCIENTIFIC STEERING GROUP (Report of the Ninth Session, Kona, Hawaii, USA, 23-25 July 1990) (WMO/TD-No. 387)
WCRP-48	SPACE OBSERVATIONS OF TROPOSPHERIC AEROSOLS AND COMPLEMENTARY MEASUREMENTS (Report of experts meeting at Science and Technology Corporation, Hampton, Virginia, U.S.A., 15-18 November 1989) (WMO/TD-No. 389) (out of print)
WCRP-49	TOGA MONSOON CLIMATE RESEARCH (Report of the 2nd session of the Monsoon Numerical Experimention Group, Kona, Hawaii, U.S.A., 26-27 July 1990) (WMO/TD-No. 392)
WCRP-50	TOGA NUMERICAL EXPERIMENTATION GROUP (Report of the 4th Session, Palisades, New York, U.S.A., 13-14 June 1990) (WMO/TD-No. 393)
WCRP-51	RADIATION AND CLIMATE (Report of the 1st Session, International Working Group on Data Management for WCRP Radiation Projects, New York City, U.S.A., 21-23 May 1990) (WMO/TD-No. 398)
WCRP-52	THE RADIATIVE EFFECTS OF CLOUDS AND THEIR IMPACT ON CLIMATE (Review prepared by Dr. A. Arking at request of IAMAP Radiation Commission) (WMO/TD-No. 399)
WCRP-53	CAS/JSC WORKING GROUP ON NUMERICAL EXPERIMENTATION (Report of the sixth session, Melbourne, Australia, 24-28 September 1990) (WMO/TD-No. 405)
WCRP-54	RADIATION AND CLIMATE (Workshop on Implementation of the Baseline Surface Radiation Network, Washington, DC, U.S.A., 3-5 December 1990) (WMO/TD-No. 406)
WCRP-55	GLOBAL CLIMATE MODELLING (Report of first session of WCRP Steering Group on Global Climate Modelling, Geneva, Switzerland, 5-8 November 1990) (WMO/TD-No. 411)
WCRP-56	THE GLOBAL CLIMATE OBSERVING SYSTEM (Report of a meeting convened by the Chairman of the Joint Scientific Committee for the WCRP, Winchester, U.K., 14-15 January 1991) (WMO/TD-No. 412)

WCRP-57 GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (Report of the 3rd session of the JSC Scientific Steering Group, Hamilton, Bermuda, 21-25 January 1991) (WMO/TD-No. 424)

WCRP-58 INTERCOMPARISON OF CLIMATES SIMULATED BY 14 ATMOSPHERIC GENERAL CIRCULATION MODELS (CAS/JSC Working Group on Numerical Experimentation, prepared by Dr. G.J. Boer et al) (WMO/TD-No. 425)

WCRP-59 INTERACTION BETWEEN AEROSOLS AND CLOUDS (Report of the Experts meeting, Hampton, Virginia, U.S.A., 5-7 February 1991) (WMO/TD-NO. 423)

WCRP-60 THE GLOBAL PRECIPITATION CLIMATOLOGY PROJECT (Report of the Fifth Session of the International Working Group on Data Management, Laurel, Maryland, U.S.A., 20-21 May 1991) (WMO/TD-No. 436)

WCRP-61 GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (Report of the Second Session of the WCRP-GEWEX/IGBP Core Project on BAHC Joint Working Group on Land-Surface Experiments, Greenbelt, Maryland, U.S.A., 3- 4 June 1991) (WMO/TD-No. 437)

WCRP-62 SEA-ICE AND CLIMATE (Report of a Workshop on Polar Radiation Fluxes and Sea-Ice Modelling, Bremerhaven, Germany, 5-8 November 1990) (WMO/TD-No. 440)

WCRP-63 JSC/CCCO TOGA SCIENTIFIC STEERING GROUP (Report of the tenth session, Gmunden, Austria, 26-29 August 1991) (WMO-TD-No. 441)

WCRP-64 RADIATION AND CLIMATE (Second Workshop on Implementation of the Baseline Surface Radiation Network, Davos, Switzerland, 6-9 August 1991) (WMO/TD-No. 453)

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