No. 45

September 1977

An occasional series reporting on U.S. and international GARP scientific, technical, and planning activities, developments, and programs, presented as a public service to the meteorological community by the American Meteorological Society through arrangements with the U.S. Committee on the Global Atmospheric Research Program of the National Academy of Sciences-National Research Council. Opinions expressed in "GARP Topics" do not necessarily reflect the point of view of the U.S. Committee.

An Analysis of GATE Aircraft Radiation Instrumentation

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Abstract

Significant differences in U.S. and U.S.S.R. aircraft measurements of hemispherical infrared irradiance were noted during GATE in-flight intercomparisons. In specific instances the downward irradiance measured by the U.S.S.R. instrument (a Kozyrev pyrgeometer) was as much as 1.5 times greater than the irradiance measured with the U.S. instrument (an Eppley pyrgeometer). A post-GATE intercomparison at Colorado State University verified these differences; the pyrgeometer measurements were compared with independent measurements obtained with an infrared bolometer and with a radiative transfer calculation. The differences noted during GATE and post-GATE intercomparisons may be attributed to differences in calibration techniques and the accurate determination of the temperature of the instrument's thermopile reference junctions. When corrections based upon this analysis were applied to the U.S.S.R. data, the maximum intercomparison differences between the U.S. and the U.S.S.R. data were <5%.

1. Introduction

During the GATE field phase, participating scientists from the United States and the U.S.S.R. became aware of significant differences between their aircraft measurements of the hemispherical infrared irradiance. Although several in-flight intercomparisons between the

U.S. and the U.S.S.R. aircraft were made during the experiment, there was insufficient time to investigate the cause of the observed differences. Subsequently, scientists from both the United States and the U.S.S.R. met at Colorado State University, Ft. Collins, Colo., during October 1975 to investigate the discrepancies noted above.

During the period of their joint investigation, the researchers sought answers to the following questions:

- 1) How reliable are preliminary aircraft hemispheric radiation data reported from GATE?
- 2) What are the physical reasons for the observed discrepancies between the data of the U.S.S.R. and the United States?
- 3) What steps may be taken to bring the two data sets into agreement?

The remainder of this report attempts to answer the above questions from the results of the joint research conducted during and after GATE by the authors.

2. Theory of operation

The theory of operation of the U.S.S.R. and U.S. pyranometers used in GATE is similar and is described by Robinson (1966). Since the pyranometer intercom-

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parison data given in Section 4 of this paper did not show large discrepancies, we shall not discuss the characteristics of the pyranometer in detail at this time.

The long-wave broad-band pyrgeometers used for the aircraft measurements made during GATE from the IL-18M aircraft of the Main Geophysical Observatory, Leningrad, are a modification of the Kozyrev net radiometers manufactured by the Leningrad Electrotechnical Engineering Institute. The detailed description and theory of operation of these radiometers are given by Kozyrev (1966), and the results of field tests of the instruments were reported by Faraponova and Timanovskaya (1966) and Faraponova (1966).

The pyrgeometers used on the U.S. aircraft were manufactured by Eppley Laboratories. These pyrgeometers were first described by Drummond *et al.* (1970). The theory of operation and the testing of these instruments from an aircraft platform were discussed by Albrecht *et al.* (1974).

The principle of operation is similar for the Kozyrev and Eppley pyrgeometers. Both consist of a thermopile shielded by a hemispheric filter of KRS-5. The data reduction equation used to obtain the long-wave irradiance values from these instruments is given as

$$L = \delta\sigma T_s^4 + V/\epsilon - k\sigma(T_d^4 - T_s^4), \quad (1)$$

where,

- δ effective thermopile emissivity;
- σ Stefan-Boltzman constant;
- T_s thermopile reference junction temperature (sink temperature);
- T_d temperature of the KRS-5 filter;
- V thermopile output of the instrument, V;
- ϵ sensitivity of the instrument, V/(W m⁻²);
- k a constant that is the relative sensitivity of the output of the instrument to differences between the filter and sink temperatures.

A detailed derivation of (1) is given by Albrecht *et al.* (1974).

Although the instruments are similar in construction, there are three principal differences between the Kozyrev aircraft pyrgeometer and the Eppley pyrgeometers used during GATE:

- 1) A white magnesium oxide coating on the thermopile surface is used in the Kozyrev sensors to block the short-wave radiation; the Eppley instruments have an interference filter deposited on the inner side of the KRS-5 dome serving the same purpose.
- 2) The data reduction equation for the Kozyrev instrument does not account for KRS-5 hemisphere and thermopile sink temperature differences, i.e., the last term in (1) is set equal to 0.
- 3) The thermopile reference junctions of the Kozyrev sensors are suspended in air inside the sensor and are provided with wire "whiskers" for heat dissipation, whereas the reference junctions of the Eppley instruments are connected to the instrument housing.

FIG. 1. Thermopile output, sink temperature, dome temperature, and blackbody temperature as a function of time for a typical calibration run of the Eppley pyrgeometer. All temperatures are measured to $\pm 0.1^\circ\text{C}$, and the thermopile output voltages are measured to $\pm 0.005\text{ mV}$.

3. Pyrgeometer calibration

The thermopile sensitivity, ϵ , and the constant k in (1) are determined by a laboratory calibration. To determine the sensitivity of the Eppley thermopile, the instrument is faced into a blackbody cavity while thermopile output, sink temperature, and dome temperature are recorded as a function of time. This calibration procedure is described in detail by Albrecht and Cox (1977).

An example of instrument output and the dome and sink temperatures as a function of time is shown in Fig. 1 for a single calibration point. Initially, the KRS-5 dome is warmer than the sink. However, when the instrument is faced into the blackbody, the dome cools relatively quickly as it loses energy to the cold blackbody whereas the thermopile sink cools much more slowly since its thermal mass is much greater. After ~ 3 min the dome and sink cool at approximately the same rate. The instrument output initially decreases rapidly and then stabilizes after ~ 3 min. This behavior is consistent with (1), which may be written in the form

$$V/\epsilon = L - \delta\sigma T_s^4 + k\sigma(T_d^4 - T_s^4). \quad (2)$$

The dominance of the $k\sigma(T_d^4 - T_s^4)$ is apparent in the variation of output voltage as a function of time as shown in Fig. 1.

Assuming that no large temperature gradients exist on the dome, ϵ in (2) may be determined by plotting the instrument output, V , at points where $T_d = T_s$ as a function of $L_{BB} - \delta\sigma T_s^4$, where L_{BB} is the blackbody irradiance (Fig. 2). In the results given here, the effective emissivity, δ , is assumed to be 1.0. A typical sensitivity value for the Eppley pyrgeometers is $\approx 0.005\text{ mV}/(\text{W m}^{-2})$.

A similar procedure was used for determining the sensitivity of Kozyrev pyrgeometers. The procedure dif-

FIG. 2. Calibration data for determination of thermopile sensitivity, ϵ , where $T_s = T_d$ for the Eppley pyrometer. The symbol L_{BB} represents the blackbody irradiance.

ferred in that the dome temperature was not obtained, and the sensitivity was determined at points where the thermopile output had stabilized. A typical sensitivity value for the Kozyrev pyrometers is ≈ 0.04 mV/(W m⁻²).

After ϵ has been determined, the constant k is determined for the Eppley instrument by plotting $(L_{BB} - 8\sigma T_s^4 - V/\epsilon)$ versus $\sigma(T_d^4 - T_s^4)$. A typical numerical value for k determined in this way is $k \approx 4.0$.

4. GATE field phase intercomparison data

A series of prescheduled intercomparisons between various aircraft were conducted during the GATE field phase. From these data, samples of which are given in Table 1, generally good agreement between both short-wave irradiance components may be seen. The upward short-wave irradiance, $K\uparrow$, data from the IL-18M aircraft tend to be $\sim 15\%$ larger than the corresponding data from the U.S. aircraft, the NCAR Sabreliner. It is encouraging that this trait appears to be consistent at all altitudes. Since a discrepancy of the same magnitude does not exist for the $K\downarrow$ measurements, one is tempted to suggest that the cosine response of the two instru-

ments may be different and that it would account for the differences in the observations. Such a tentative conclusion is supported by results reported previously by Hanson (1974).

Measurements of the downward infrared component, $L\downarrow$ (before correction), showed the largest inconsistency in the intercomparison data shown in Table 1. One readily sees from these data that the discrepancy is altitude dependent, the IL-18M values being significantly greater than the Sabreliner values at higher altitudes. A similar discrepancy was noted between the $L\downarrow$ values measured from the U.S. C130 and the IL-18M. The $L\downarrow$ (after correction) values shown in Table 1 will be discussed later in this paper.

5. Post-GATE intercomparison data

Table 2 summarizes the results of a series of measurements made on 4 November 1975 in Ft. Collins, Colo. This series of intercomparison measurements between the Eppley and the Kozyrev instruments was conducted under varying degrees of solar illumination and ventilation of the instruments. Ventilation was supplied by exposing the appropriate instrument to a stream of compressed air. The instruments were shaded from direct solar illumination by using small circular disks.

The sky was virtually cloud free and the data were collected from 1403 LST to 1716 LST. The data were reduced by using calibration constants derived as explained in Section 3 and then applying (1) from Section 2. The results obtained at night and when the instruments are ventilated and shaded are consistent with the field phase intercomparison in that the Kozyrev values are significantly greater than the Eppley values.

At 1716 LST an infrared bolometer (2° field of view) with a spectral band pass of $1.8\text{--}26\ \mu\text{m}$ was used to measure independently the infrared radiance at a few zenith angles. Measurements were made after sunset, thereby eliminating any possible solar contamination. An integration over 2π sr neglecting any azimuthal variation yielded a downward irradiance value of 247 W m^{-2} . Since sky conditions were uniform during this measurement,

TABLE 1. Intercomparison of radiation data from U.S.S.R. IL-18 M (IL) and U.S. Sabreliner (S) aircraft, 30 July 1974.

Altitude, m	Time, GMT	Downward Long Wave, $L\downarrow$, W m ⁻²					Downward Short Wave, $K\downarrow$, W m ⁻²			Upward Long Wave, $L\uparrow$, W m ⁻²					Upward Short Wave, $K\uparrow$, W m ⁻²		
		S	IL*	IL†	S/IL*	S/IL†	S	IL	S/IL	S	IL*	IL†	S/IL*	S/IL†	S	IL	S/IL
6100	12:48:30 to 12:54:15	154	224	150	0.69	1.027	1202	1155	1.04	367	309	336	1.19	1.093	111	127	0.87
3050	13:15:00 to 13:19:00	279	333	300	0.84	0.930	1110	1080	1.03	395	378	406	1.04	0.974	85	102	0.83
1525	13:35:15 to 13:39:45	340	378	345	0.90	0.986	1037	1002	1.03	388	403	381	0.96	1.018	60	72	0.83
915	14:01:00 to 14:03:45	352	392	367	0.90	0.959	1003	960	1.04	387	409	389	0.95	0.995	44	53	0.83

* Before correction.

† After correction.

TABLE 2. Post-Gate intercomparison between the Kozyrev (K) and Eppley (E) data gathered at Ft. Collins, Colo., on 4 November 1975.

Local Time	Downward Long Wave, $L\downarrow$, W m^{-2}		Assumes $T_d = T_s$, W m^{-2}	Downward Long Wave, $L\downarrow$, W m^{-2}		Incoming Solar Irradiance, W m^{-2}
	K*	K†		E†		
1423	409	339	326	230		370–384
1430	340	247 S	263S	274		370
1436	403	327	264S	279		350
1441	349	253	322	205		336
1446	378	298	308	225		332
1458	394	321	275V	245		285
1505	345	278 V	310	202		260
1512	349	275 V&S	309	214		242
1519	399	330	272 V&S	269		232
1716	349	280	281 N	264		0

Additional measurements with a bolometer at 1716 LST (1.8–26 μm) gave $L\downarrow = 247 \text{ W m}^{-2}$, and computation using radiosonde data from Denver at 0000 GMT gave $L\downarrow = 263 \text{ W m}^{-2}$. S is shaded, V is ventilated, and N is night.

* Before correction.

† After correction.

‡ Uses $k(T_d^4 - T_s^4)$ in equation (1).

the error in this measurement should be no greater than $\pm 10 \text{ W m}^{-2}$.

In addition to the data noted above, the 0000 GMT radiosonde data from Denver, Colo., were used in a computation of $L\downarrow$ at the surface. The computation technique described by Cox (1973) yielded an $L\downarrow$ value of 263 W m^{-2} . This calculated flux should not differ from the actual flux by more than $\pm 10 \text{ W m}^{-2}$ for the relatively dry, cloud-free conditions that existed when the measurements were made.

6. Analysis

The differences noted between the measurements made by the Eppley and the Kozyrev instruments are significantly greater than the 5% inaccuracy that would be expected for these pyrgeometers. Since the basic design of these instruments is similar, it is reasonable to expect that the discrepancies in the measurements may be related to the differences in the instrument construction identified in Section 2 and the differences in the calibration procedures discussed in Section 3. In this section the possible errors that might be associated with these differences are discussed.

The spectral characteristics of the Eppley and Kozyrev pyrgeometers are slightly different, as shown in Fig. 3. The principal difference is that the Kozyrev instrument is relatively sensitive to radiation in the wavelength interval of 2.0–4.0 μm , whereas the Eppley instrument has virtually no response at these wavelengths. Consequently, the Kozyrev instrument will be slightly sensitive to solar radiation. Using the spectral distribution of direct solar energy (Kondratyev, 1969), one can calculate the maximum overestimate (zenith angle of 0) of the flux measured by the Kozyrev instrument due to solar

FIG. 3. Relative response of the Kozyrev (curve I) and Eppley (curve II) pyrgeometers as a function of wavelength. (After Kozyrev, 1966, and Albrecht *et al.*, 1974.)

radiation. This maximum overestimate is given below as a function of height for clear sky conditions:

Height, km	Overestimate, W m^{-2}
0.5	10
3	13
6	16

These estimates clearly indicate that the differences in the spectral responses of the instruments cannot account for the differences noted during the intercomparisons. This conclusion is consistent with the observations (see Table 2) since the Kozyrev values obtained at night are also significantly greater than the Eppley values.

Another difference between the Kozyrev and the Eppley pyrgeometers is that the Kozyrev instrument does not account for the $k\sigma(T_d^4 - T_s^4)$ term, which appears in the data reduction equation, (1). Under calm daytime conditions this term may be significant since the KRS-5 may become warmer than the instrument housing due to the absorption of solar radiation. This effect is clearly demonstrated by the results shown in Table 2. Assuming that the actual $L\downarrow$ value was constant through the period, one notes an obvious dependence of the $L\downarrow$ values on the incident solar radiation by comparing values of $L\downarrow$ when each instrument is shaded and unshaded. This dependence is apparently a heating effect since a similar dependence is noted for the ventilated and unventilated values. Furthermore, in the case of the Eppley instrument, the attempt to correct for this effect by the dome-sink temperature difference resulted in an overcorrection. This may be explained by the fact that the dome temperature was measured at one point on the dome by a thermistor; lacking ventilation, temperature gradients appear on the dome and the single temperature transducer is not representative of the dome temperature.

Taking the Kozyrev shaded, ventilated and shaded, and ventilated data, one notes that all three cases yield $L\downarrow$ values in the interval $340\text{--}349 \text{ W m}^{-2}$; the nighttime value was also 349 W m^{-2} . It, therefore, appears that even though solar heating of the dome is important in

still air, even moderate ventilation will significantly suppress this effect. With the ventilation offered by the slipstream of an aircraft, this effect should be virtually eliminated and should not be a factor in causing the large discrepancies noted during the GATE intercomparisons.

The differences in the placement of temperature transducers within the instrument may account partially for the differences in the measurements. When making measurements with the Kozyrev pyrgeometer, it is assumed that the reference junctions are at the same temperature as the instrument housing. This assumption may result in erroneous measurements since the reference junctions and the housing are not in direct thermal contact. In the case of the Eppley instrument, the reference junctions are attached to an internal sink of the instrument and the temperature measurement is made at the point where this contact is made.

To illustrate the effect that this difference might have on the measurements, it may be noted that when the pyrgeometer is viewing the downward irradiance the thermopile surface is cooler than the body of the instrument (thermopile output is negative). Consequently, one would assume that the reference junction temperature of the Kozyrev instrument would be less than or equal to the instrument housing temperature. The more negative the output is (the cooler the thermopile surface), the greater the difference there would be between the reference junctions and the instrument housing temperature. Hence, if the housing temperature is used to obtain L , the results may be erroneously high when the thermopile output is negative. A similar effect might also be expected when measuring the upward irradiance, although in this case the thermopile is warmer than the reference junctions.

Differences between the Eppley and the Kozyrev measurements may also be due to the calibration procedure. When the Kozyrev pyrgeometer is calibrated, the dome temperature is not monitored and the sensitivity is determined at points where the thermopile output stabilizes (cf., Fig. 1). Under these conditions, the $k\sigma(T_d^4 - T_s^4)$ term may be large (and negative), so that its neglect results in an erroneously large thermopile sensitivity. In the case of the Eppley instrument, the sensitivity determined in this way would be 60% greater than the sensitivity determined when $T_d = T_s$.

In terms of the measurement of the downward irradiance (thermopile output is negative) the larger sensitivity would result in an erroneously large irradiance as shown by (1). For example, if the measurements made on 4 November with the Eppley instrument were made using the larger sensitivity, the measured value would be increased by $\sim 40 \text{ W m}^{-2}$. Again, a similar effect would also occur when measuring the upward irradiance. In this case, however, the thermopile output will be positive, so that an overestimate in the sensitivity may result in an erroneously low measurement, particularly when the thermopile output is large.

Keeping these considerations in mind and assuming

FIG. 4. Kozyrev pyrgeometer output as a function of the instrument housing temperature.

that the thermal properties of the KRS-5 domes in both the Kozyrev and the Eppley pyrgeometers are basically the same, an attempt was made to recalculate the Kozyrev pyrgeometer sensitivity using the same approach as that used for the calibration of the Eppley instruments. It was assumed that the equilibrium point $T_d = T_s$ (see Section 3) is reached by the Kozyrev pyrgeometer with a time lag equal to that of the Eppley. The instrument sensitivity was then determined according to the technique stated in Section 3. The sensitivity calculated in this way was 36% lower than that obtained originally.

Next, an attempt was made to determine any residual error due to temperature differences between the instrument housing and the thermopile reference junctions. For this purpose, the Kozyrev pyrgeometer was warmed up or cooled down and then faced into the blackbody cavity, the blackbody itself being at room temperature. The IR flux (presumably equal to the blackbody irradiance) was then calculated using the new sensitivity value as the instrument cooled down or warmed up.

The results of these calculations, shown in Fig. 4, indicate that the calculated IR flux is significantly higher than that emitted by the blackbody. It is interesting to note the quick drop of calculated flux in the case of the warmed-up instrument, which then gradually rises above the level of blackbody irradiance. One can interpret this as the influence of the dome, which cools quickly in relation to the instrument housing and then gradually comes into thermal equilibrium with the slowly cooling instrument itself.

If it is assumed that under stable conditions the discrepancy between the calculated flux and the actual blackbody irradiance is merely an instrument offset, the data in Fig. 4 indicate that this offset is 47 W m^{-2} .

With the new sensitivity data and the offset noted above, the data for the Kozyrev pyrgeometer for both GATE (Dakar) and post-GATE (Ft. Collins) intercomparisons were recalculated. The results of such recalculations are given in Tables 1 and 2, under the headings with daggers (denoting after correction).

One may readily see from this comparison that the proposed correction scheme yields very good agreement for the intercomparisons. Values are within 10% of one another for the GATE in-flight intercomparisons and to within at least 5% for the post-GATE ground intercomparisons.

7. Concluding remarks

In the introduction, three questions that this paper proposed to answer were explicitly stated. In this section we shall restate these questions and offer our best answers to them.

- 1) How reliable are preliminary aircraft hemispheric radiation data reported from GATE?

From the intercomparison data gathered during GATE, downward solar irradiance values observed by U.S. and U.S.S.R. aircraft showed very good agreement. In general, upward solar irradiance values observed by U.S. aircraft are systematically smaller by $\sim 15\%$. This difference is most likely due to the differences in the cosine responses of the two instruments.

Most intercomparison data show acceptable agreement between observations of upward long-wave irradiance; however, there are dramatic differences between observations of downward long-wave irradiance, $L\downarrow$. The preliminary data of $L\downarrow$ from the U.S.S.R. aircraft appear to be too large.

- 2) What are the physical reasons for the observed discrepancies between the $L\downarrow$ data of the U.S.S.R. and the United States?

There are apparently three separate reasons that may account for the differences in the observations of $L\downarrow$. First, in the U.S.S.R. instrument, the KRS-5 dome and sink temperatures are assumed to be equal. Although the laboratory data collected in this study indicate this to be a minor problem, it may still account for some of the observed discrepancy.

Second, the dome-sink temperature difference during calibration may introduce an error into the determination of the sensitivity factor used in the data reduction equation. It is important that the sensitivity factor be resolved from the data for which the equivalence of dome and sink temperatures is assured.

Third, in the Kozyrev instrument, the temperature used in the $\delta\sigma T_s^4$ term in the data reduction equation is measured on the body of the instrument. In fact, the temperature in the reduction equation is the thermopile reference junction temperature. If these two temperatures are significantly different, as seems likely under conditions of low $L\downarrow$ values, significant overestimates of $L\downarrow$ would result.

- 3) What steps may be taken to bring the two data sets into agreement?

On the basis of research presented in this paper, the authors suggest that the values of the IL-18M IR actinometric measurements be reduced according to the following procedure:

- 1) The sensitivity value should be lowered by 36% for both upward and downward looking pyrgeometers.
- 2) Measurement data should be reduced according to (1) using the new sensitivity values.

- 3) The values obtained in step 2 should be further reduced by 47 W m^{-2} .
- 4) The new values of IR fluxes should be presented to the Radiation Subprogram Data Center (RSDC) at the Main Geophysical Observatory, Leningrad. However, in agreement with recommendations of Subgroup 3 of the Informal Planning Meeting for the GATE Radiative Subprogram (Leningrad, U.S.S.R., June 1975), the original data of the IL-18M actinometric measurements should be preserved by the RSDC.

Acknowledgments. The research reported in this paper has been supported by the Global Atmospheric Research Program, National Science Foundation, under grant OCD 72-01691 AO3 and OCD 74-21678. The authors wish to express their sincere gratitude to the NOAA GATE Project Office, to the U.S.S.R. Hydrometeorological Service, to Prof. E. Borisenkov, Director of the Main Geophysical Observatory in Leningrad, and to K.Ya. Kondratyev, Head of the Department of Atmospheric Physics, Leningrad University, for making possible the post-GATE joint research activities reported in this paper. We also gratefully acknowledge the cooperation and support of the NCAR Research Aviation Facility.

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