Compatibility of Meteorological Rocketsonde Data as Indicated by International Comparison Tests

FREDERICK G. FINGER AND MELVYN E. GELMAN

National Meteorological Center, NOAA, Washington, D. C. 20233

FRANCIS J. SCHMIDLIN

National Weather Service, NOAA, Wallops Island, Va. 23337

ROBERT LEVITON

Air Force Cambridge Research Laboratories, Bedford, Mass. 01730

BRUCE W. KENNEDY

U. S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, N. M. 88001

(Manuscript received 27 December 1974, in revised form 29 May 1975)

ABSTRACT

Under the auspices of the Commission for Instruments and Methods of Observation of the World Meteorological Organization, meteorological rocketsonde intercomparisons took place at Wallops Island in March 1972 and at the Guiana Space Center, French Guiana, in September 1973. France, Japan and the United States participated in the Wallops tests, and France, the United Kingdom, the Union of Soviet Socialist Republics and the United States participated in the Guiana tests. Measurements were made during the day as well as at night.

Comparisons are presented of temperature and wind data obtained by the different rocketsonde systems over the altitude region from 25 to 80 km. Results indicate generally good compatibility among temperatures obtained below approximately 50 km. Above that level, biases increasing with height are evident. Temperature adjustments are derived, which, when applied to operational rocketsonde data, would in the mean achieve compatibility for synoptic analyses and other uses. Comparisons among wind observations indicate generally good agreement below approximately 60 km. However, some significant problem areas are pointed out and discussed.

The Guiana series of observations also provided valuable information on the diurnal temperature change at stratospheric and mesospheric levels. An evaluation of this aspect is presented, and results are compared with those predicted by tidal theory.

1. Introduction

Meteorological rocketsonde systems of several different types are used regularly by countries throughout the world to obtain atmospheric temperature and wind in the altitude layer from about 25 to 70 km. There are significant differences in the physical characteristics of the rocketsonde systems developed and used by various countries. There are also differences in the techniques used for deriving meteorological parameters from the measurements. Operational meteorological rocketsonde information has been exchanged through international agreement for a number of years, and users have long recognized the need for comparison tests to gain information on the compatibility of information from the various countries.

The Commission for Instruments and Methods of Observations (CIMO) of the World Meteorological Organization planned and carried out the necessary comparisons over the course of several years. Because of organizational and logistical problems associated with an effort of this type, the actual comparisons were held in two parts. The first part took place at the National Aeronautics and Space Administration Wallops Flight Center, Wallops Island, Va. (37°51′N, 75° 29′W) during March 1972, with France, Japan and the United States participating. The intercomparisons were completed at the French Guiana Space Center (CSG) (5° 12′N, 52° 25′W) from 20 September to 1 October, 1973. France, the Union of Soviet Socialist Republics, the United Kingdom and the United States took part in this second phase.

The major purpose of this paper is to present results of the two experiments which comprised the CIMO rocketsonde intercomparisons. (The observed data are available from the Permanent Secretary, CIMO, World Meteorological Organization, Geneva.) We shall attempt to interpret the results in order to gain some estimate of the compatibility of rocketsonde data, since this knowledge is needed for meaningful depiction of stratospheric-mesospheric circulation.

2. Description of rocketsonde systems

Rocketsonde systems provide a continuous vertical measurement of temperature and wind. Instruments are propelled to high altitude by meteorological rockets. When the payload is ejected, it is slowed down by a retardation device. As the payload descends, a continuous record of position versus time is obtained by tracking with radar or similar system. A simultaneous continuous trace of temperature versus time is also obtained, which provides a profile of temperature versus height. In practice the vertical temperature and wind profiles are reported at regular altitude intervals (i.e., each whole kilometer). The parameters compared in this paper are temperature and wind at geometric altitudes between 25 and 80 km. Data were provided by each participating country in a format comparable at whole-kilometer levels.

We will describe a few of the outstanding characteristics of each instrument involved in these tests in order to highlight the differences. For a more complete description of these systems, the reader is advised to study the cited references. To our knowledge, the systems and data reduction methods described herein are still in use as of the writing of this paper. However, research is continuing at a fairly rapid rate by each country in order to develop improved equipment and methods of data processing.

a. France

The French meteorological sounding rocket uses a Super Arcas motor and a DMN payload. Temperatures and winds can be measured to an altitude of approximately 80 km (Villain and Loitiere, 1972). The DMN retardation device uses a hemispherically shaped parachute made of silk, but metalized to aid radar tracking. Radar position data allow the derivation of wind and temperature height profiles. Wind data are corrected to remove ballistic motion and fall velocity effects from the measurements.

The sonde contains two temperature sensors. The primary sensor is a gold-coated tungsten wire. The second sensor is a flat nickel plate which is used below 60 km only if the primary sensor fails. Temperature measurements are corrected for possible errors induced by convection, conduction, radiation, electrical heating, and aerodynamic heating. Total corrections for these factors lower measured temperature values about 17 to 53°C at 70 km, 8 to 18°C at 60 km, and approximately 3°C at 50 km.

b. Japan

The Japanese vehicle (MT-135-P) is a solid-propellant, single-stage rocket designed to reach 50 to 60 km altitude where the nose cone separates and the parachute and transmitter are deployed (Tamaki *et al.*, 1965). The Echosonde instrument contains a nickel-iron wire as the temperature sensing device. Temperature measurements are corrected for aerodynamic heating, radiation, lag and electrical heating (Yata, 1970). The total correction lowers 60 km temperatures approximately 22°C. Wind data are also corrected for fall velocity and ballistic motion effects.

c. Union of Soviet Socialist Republics

The M-100 rocket system, weighing about 480 kg, uses a two-stage, unguided, solid-fuel rocket motor with a payload designed to measure temperature, pressure and wind (Izakov *et al.*, 1967; NASA, 1972). After the first-stage rocket motor burns out at about 3 km, the second-stage motor ignites and continues to apogee, near 100 km. Various sensors are uncovered following nose cone ejection at about 60 km during ascent. The parachute is also deployed on the ascent and, after passing apogee, acts as a stabilizing drag on the descent to about 65 km, where wind sensing begins. Sensor information is telemetered to the ground and a transponder is used to determine the payload's position.

Temperature is measured by two pairs of resistance-wire thermometers. Measurements are subjected to a correction scheme which compensates for aerodynamic heating effects, lag, emissivity, self-heating, conduction, and long- and shortwave radiational heating. These correction factors vary greatly with altitude and from one sounding to the next, depending principally on aerodynamic heating due to fall velocity. Although the corrections are generally not stated explicitly, the magnitude approximates 200°C at 60 km. Wind data are also corrected for fall velocity effects.

d. United Kingdom

The SKUA rocket (Almond, 1965) is capable of reaching heights greater than 70 km. The standard meteorological payload for the SKUA includes a radar-reflecting parachute for wind measurements. The temperature sensor is a flat, double open spiral of tungsten wire. Measured temperatures are corrected for aerodynamic heating and radiation effects (Mason and Acres, 1972). The greatest single correction applied to the SKUA temperature measurements compensates for possible solar radiation effects. Because of the difficulty in estimating the radiation effect with great accuracy, the SKUA has in the past been mainly used during nighttime hours. Total corrections vary from 17 to 40°C at 70 km, 6 to 15°C at 60 km, and 1 to 5°C at 50 km.

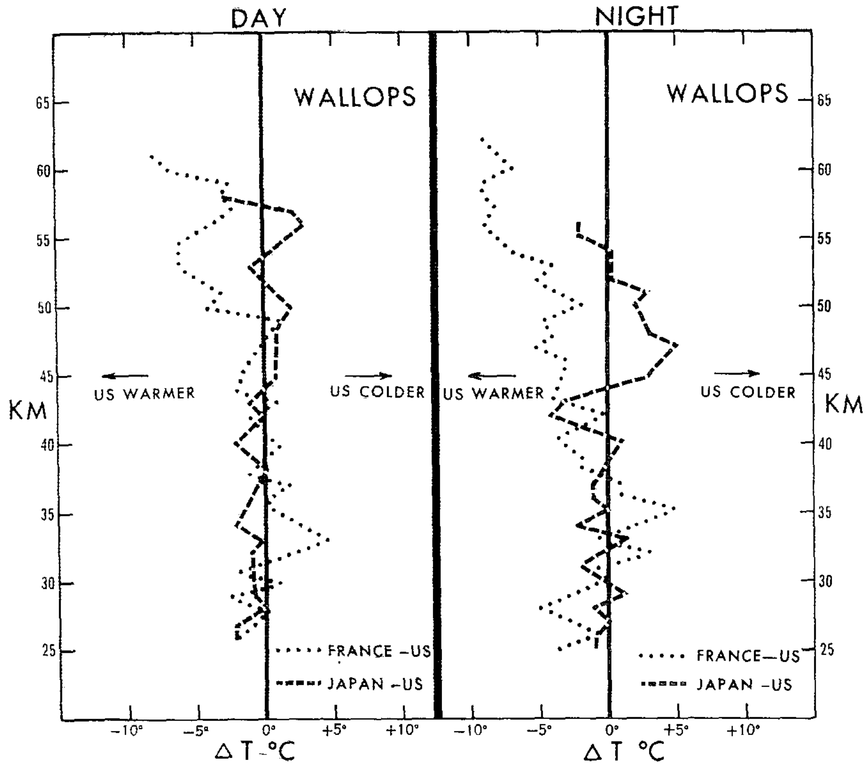

Fig. 1. Averages of differences between temperatures measured by rocketsondes of France and Japan versus U. S. measurements at Wallops Island, Va., March 1972.

c. *United States*

The Loki Datasonde (used at the Wallops test) and Super Loki Datasonde (used at CSG) measure atmospheric temperatures and winds as a function of altitude to near 60 and 70 km, respectively (United States, 1973). During the launch sequence the motor burns for approximately 2 s at which time the dart separates from the rocket motor and coasts upward to apogee. Ejection of the payload at apogee results in deployment of the radar reflective retardation device called a Starute. Wind information is derived from the differential position of the target over a fixed altitude increment utilizing computer reduction techniques. The wind information is corrected for lag response of the system to changes in wind velocity at the various altitudes.

The Datasonde instrument employs a small bead thermistor mounted on a thin-film mylar loop to measure temperature. These measurements are corrected for aerodynamic heating, lag, emissivity, and long- and shortwave radiation (Krumins and Lyons, 1972). The total correction varies from 12 to 39°C at 70 km to about 2°C at 50 km.

3. Wallops test

At the Wallops Island comparison tests, seven sets of daylight and three sets of nighttime observations were taken. However, because of system malfunctions the number of valid comparisons actually made was somewhat limited—seven between the United States and Japan (five day and two night), five between the United States and France (three day and two night), and four between the three systems (three day and one night).

The mean differences of observed temperature for the daytime and nighttime sets as a function of height are shown in Fig. 1. The reference employed for the computations were those observations made by the U.S. instrument—not as a standard, but only for convenience. Although sample size for night observations was too small for meaningful root mean square values to be calculated, the good consistency of individual set differences indicates the representativeness of mean values. The Japanese measurements appear to be generally compatible with those of the United States.

Some incompatibility between the French and United States temperature observations can be noted at the higher levels. Mean differences during the day increase above 50 km to a value of 8°C at 61 km with French-measured temperatures lower than those of the United States. For nighttime observations, differences become apparent above 40 km, steadily increasing to a value of 9°C at 62 km.

Winds were measured at essentially the same heights as temperatures. No overall bias was noted, but the

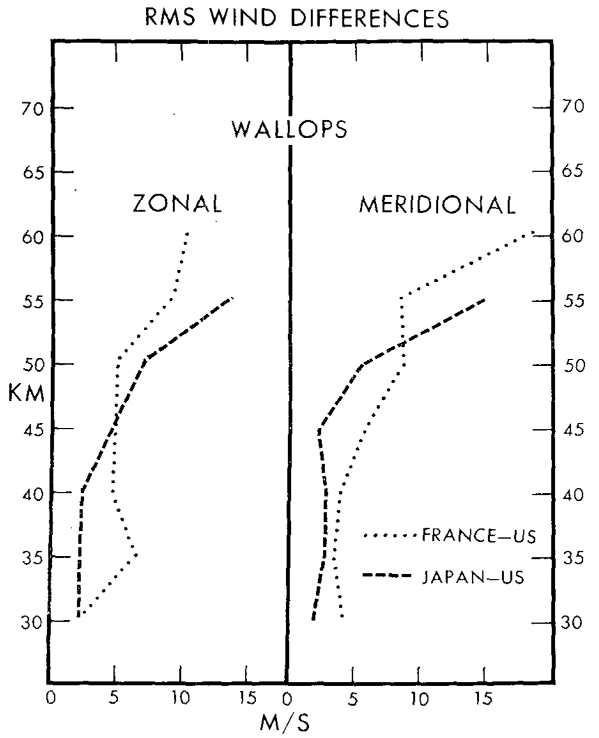

FIG. 2. Root mean square of the component wind differences for the Wallops Island comparisons.

random variability among the measurements increased with altitude. The rms differences for day and night measurements taken together are shown in Fig. 2, again with respect to the U. S. measurements. Differences of both the zonal and meridional components are less than 10 m s^{-1} up to 50 km, but increase rather sharply at the higher levels.

4. CSG comparisons

The comparisons at the Guiana Space Center took place from 20 September to 1 October, 1973. While the French, U. K. and U. S. operations were conducted from the CSG range, the ship *Korolev*, anchored a few kilometers from the range, was used for U.S.S.R. launches. Each of the four participating countries launched 13 meteorological rocketsondes, six near local noon and seven near midnight. The flight schedule, as well as performance information, can be found in Table 1. The day-night type schedule was followed for several reasons. It was rather important that each rocket type be tested under some of the conditions in which it is normally used. For example, the U. K. and U. S. S. R. launches are generally accomplished during darkness hours (to minimize solar radiation effects) and the others during daylight hours (near local noon). It was hoped that day-night launches might also yield important information on the diurnal variation of temperature. Four high precision radars were available at CSG, making it possible to complete each set of four observations within 1 h, thus minimizing effects from real atmospheric changes.

a. Wind

Winds are derived from radar tracking of retardation devices and payloads in the descent stages. U. S. S. R. tracking was accomplished with radar on the *Korolev* while all others were tracked by radars from CSG. On one occasion a U. S. S. R. payload was tracked by both U. S. S. R. ship and CSG radars, with the results indicating good compatibility between the two sets of radar measurements. Radar incompatibility could thus be discounted as a significant source of wind differences noted below.

Fig. 3 shows component wind profiles from one set of measurements. This set is generally representative of the others. Large-scale features as well as many of smaller vertical scale were outlined similarly by the French, U. K. and U. S. systems. However, there are significant differences apparent in the U. S. S. R. reported wind profiles above 40 km. In Fig. 3 this difference is especially apparent around 50 km where the U. S. S. R. zonal wind is opposite in direction from the others. Fig. 4 shows the rms wind component differences for all sets of observations. French and U. S. rms wind

TABLE 1. Flight schedule and performance for CSG comparisons.

Date		France	U.S.S.R.	U.K.	U.S.
20 Sept.	time[1]	1354	1440		1349
Day	temp-wind[2]	73–73	77–70		69–69
21 Sept.	time	0332	0420	0344	0328
Night	temp-wind	74–74	80–70	35–27	70–73
21 Sept.	time		1520	1539	1513
Day	temp-wind		80–70	65	58–58
22 Sept.	time	0437	0410	0431	0402
Night	temp-wind	74–74	68–63	69–69	74–70
24 Sept.	time	1715	1720		1710
Day	temp-wind	73–73	79–65		70–70
25 Sept.	time	0056	0030	0051	0019
Night	temp-wind	77–77	78–42	70–70	70–74
25 Sept.	time	1840	1810	1835	1800
Day	temp-wind	70–70	77–66	70–70	70–70
26 Sept.	time	0106	0020	0101	0139
Night	temp-wind	70–70	78–45	64–64	68–68
26 Sept.	time	1442	1410	1435	1404
Day	temp-wind	72–72	80–66	65–65	67–67
27 Sept.	time	1426	1410	1420	1458
Day	temp-wind	73–73	80–60	55–66	70–74
28 Sept.	time	0311	0240	0306	0233
Night	temp-wind	72–72	80–40	70–70	70–73
29 Sept.	time	0329	0301	0324	0252
Night	temp-wind	73–73	78–65	66–68	70–73
1 Oct.	time	0408	0340	0402	0330
Night	temp-wind	73–73	80–62	53–53	–73

[1] Time of observation in GMT. Substract 3 h for local French Guiana time.
[2] Highest altitude for temperature-wind data.

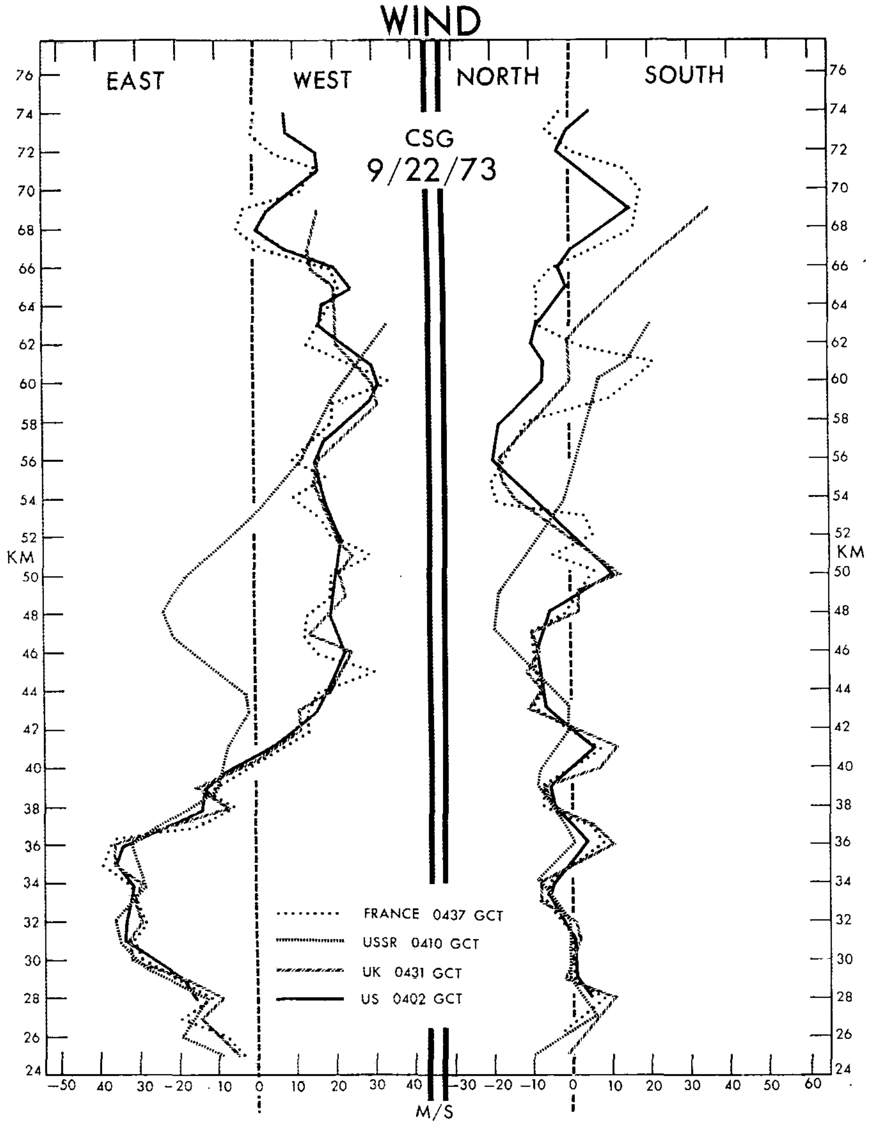

FIG. 3. Zonal and meridional wind components (south and west positive) measured by France, U. K., U. S. S. R. and U. S. on 22 September 1973 for the CSG comparisons.

differences are within approximately 10 m s^{-1} at all levels, with U. K.-U. S. wind differences meeting this test below approximately 60 km. U. S. S. R. winds show increasingly large incompatibility above 35 km. Soviet scientists indicated that possible reasons for the wind sensitivity problem at the higher levels concerned the high fall velocity of the instrument and parachute design. This general problem is being investigated by U. S. S. R. researchers.

b. *Temperature*

One set of representative temperature measurements is illustrated in Fig. 5. The French, U. K. and U. S. profiles outline temperature features similarly. However, the U. S. S. R. profile is considerably different from the others and lacks small-scale detail. Average differences were computed for the four temperature measurements taken in each set, and the values for each whole kilometer between 25 and 70 km were summarized separately for day and night soundings.

Average nighttime differences (Fig. 6) up to about 45 km remain well within ±5°C, with no significant bias apparent. Above 45 km French, U. K. and U. S. measurements still appear generally compatible, despite occasional mean differences larger than 5°C. However, the average differences between U. S. S. R. and U. S. measurements increase steadily above 45 km, reaching approximately 20°C above 65 km.

Standard deviations about the mean nighttime temperature differences (Fig. 6) at 5 km intervals are shown in Table 2. All values for the French and U. K.

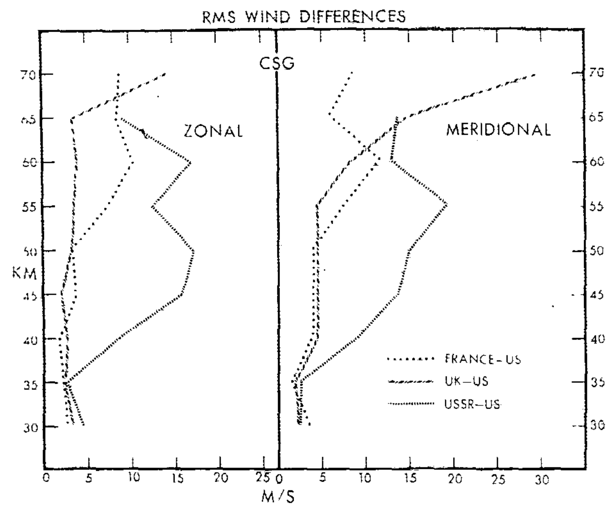

FIG. 4. Root mean square of the component wind differences for the CSG comparisons.

differences are within 5°C. However, those for the U. S. S. R. are significantly larger than the others and steadily increase with altitude.

Daytime mean temperature differences are shown in Fig. 7 and standard deviations are given in Table 2. Again the U. K.-U. S. differences suggest good overall compatibility at all levels, with apparently random values of less than ±5°C. French-U. S. differences, however, increase with height above 55 km. These results, indicating French temperature measurements to be increasing lower than those of the U. S., were somewhat puzzling, since evaluations from the Wallops test indicated the opposite trend. French experimenters (B. Loitiere, 1974)[1] indicated that a different method was used for the two tests in correcting the French temperature measurements. The altered method was necessitated for the Wallops tests by abnormally large fall velocities of the French sonde. The correction method used for the CSG tests is considered by the French to be the proper one, and that method is being used consistently for all operational soundings. U. S. S. R.-U. S. day differences are generally similar to those at night up to about 65 km, with the U. S. S. R. temperatures significantly lower than those measured by the U. S. system. However, above 65 km the differences diminish sharply.

Fig. 8 shows temperatures reported from each system at CSG at six altitudes from 30 to 70 km. There are only slight trends of temperature at any level throughout the time period of the tests. However, there are apparent differences in the temperatures measured during the day as compared to those measured at night. The subject of evaluating the magnitude and sense of the day-night differences will be treated in the next section. It was, however, important to recognize that

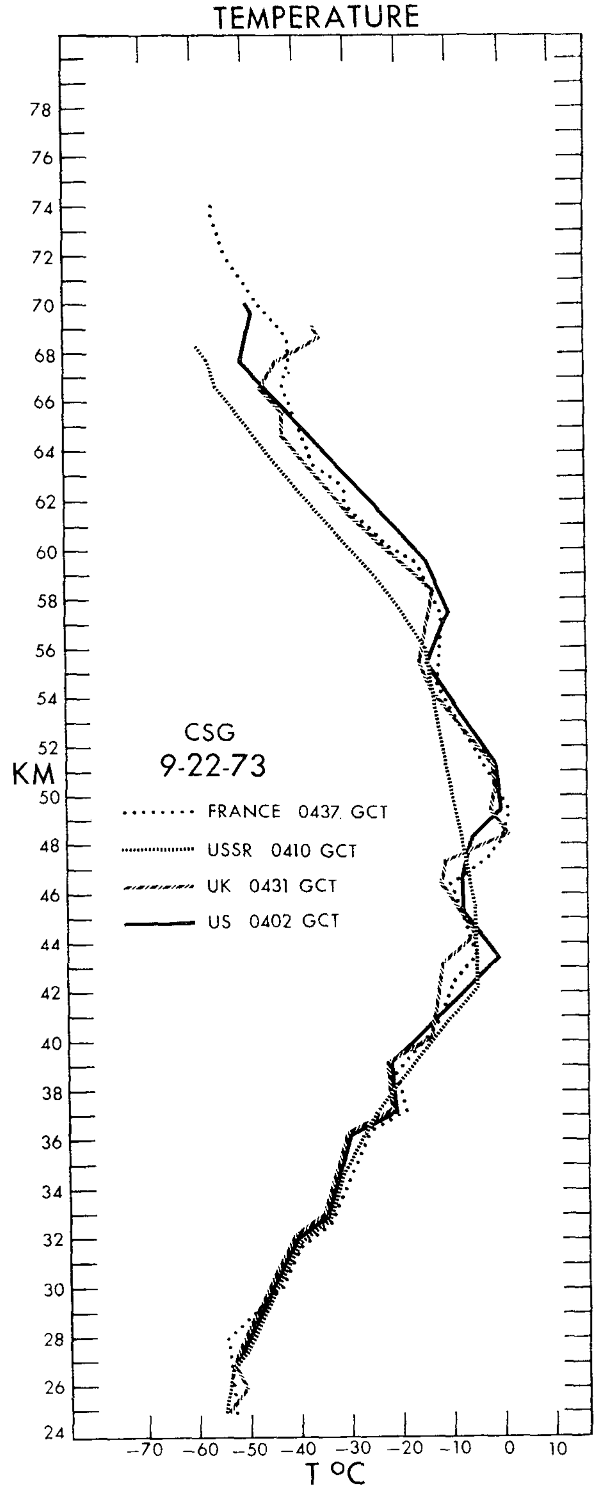

FIG. 5. As in Fig. 3 except for temperature.

there was a day-night difference. It was primarily for this reason that daytime and nighttime differences were summarized separately.

[1] Private communication.

TABLE 2. Standard deviation of mean temperature differences (°C) with sample sizes *n*.

Height (km)	Night						Day					
	Fr−US	*n*	USSR−US	*n*	UK−US	*n*	Fr−US	*n*	USSR−US	*n*	UK−US	*n*
70	5	5	13	4			15	3	7	5		
65	4	6	11	6	3	4	5	5	10	6		
60	3	6	8	6	4	5	3	5	8	6		
55	2	6	7	6	3	5	2	5	6	7	5	3
50	3	6	4	6	2	5	1	5	2	6	2	3
45	1	4	4	6	1	5	3	5	3	6	1	3
40	3	6	4	6	1	5	2	5	3	6	2	3
35	1	6	1	6	1	6	3	5	3	7	1	3
30	1	6	2	6	1	6	1	5	2	7	1	3

c. *Day-to-night temperature differences*

As noted previously, it was hoped that some information regarding the real diurnal variation of temperature could be obtained from the sample of soundings taken at approximately 12 h intervals (9–15 h). From Fig. 8 it is quite evident that mean day and night temperatures differ significantly; and this trend is shown by observations from all rockets. To the extent that the measurements are corrected for radiation errors, average 12 h temperature differences may be interpreted as (at least partly) a result of the real diurnal temperature variation of the atmosphere over CSG during late September.

Mean values of the day-night differences (computed at each whole kilometer from 25 to 80 km) are shown in Fig. 9. The most striking feature of this figure is the change in sign of the differences at various levels. Noon temperatures are indicated to be higher than midnight temperatures between approximately 34 to 45 km, with a noon-midnight range of approximately 6°C at 39 km. Midnight temperatures higher than noon temperatures are indicated around 45 to 55 km, with a maximum noon-midnight temperature range of approximately 7°C at about 48 km. Above 60 km the trends of the various instruments diverge.

It is interesting to compare these results with information derived from theoretical calculations of

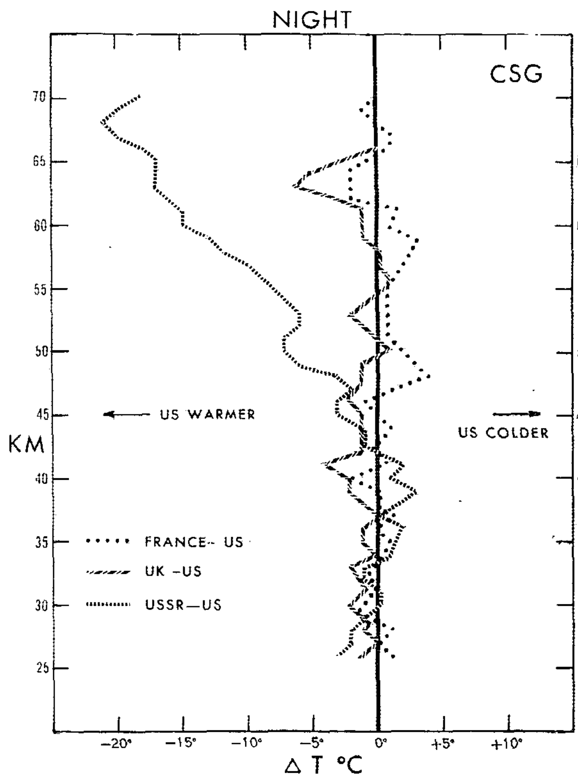

FIG. 6. Averages for night observations of differences between temperatures measured by rocketsondes of France, U.K. and U.S.S.R. versus U.S. measurements at CSG.

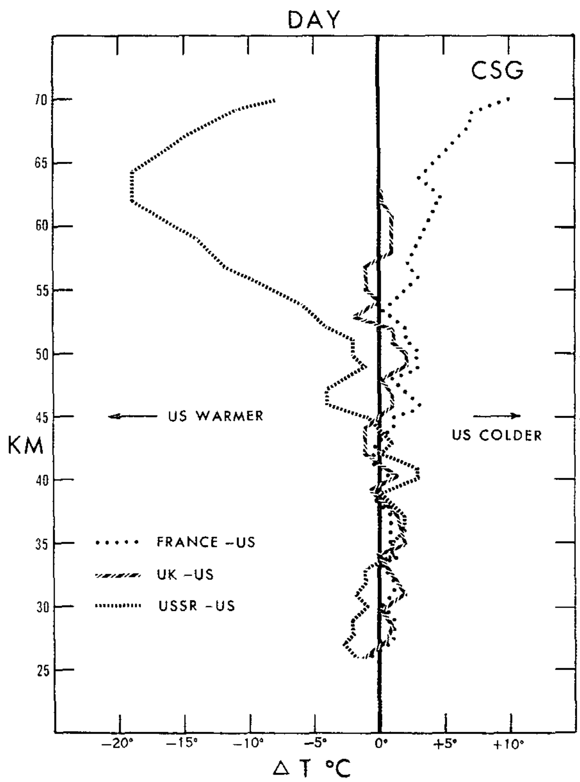

FIG. 7. As in Fig. 6 except for daytime observations.

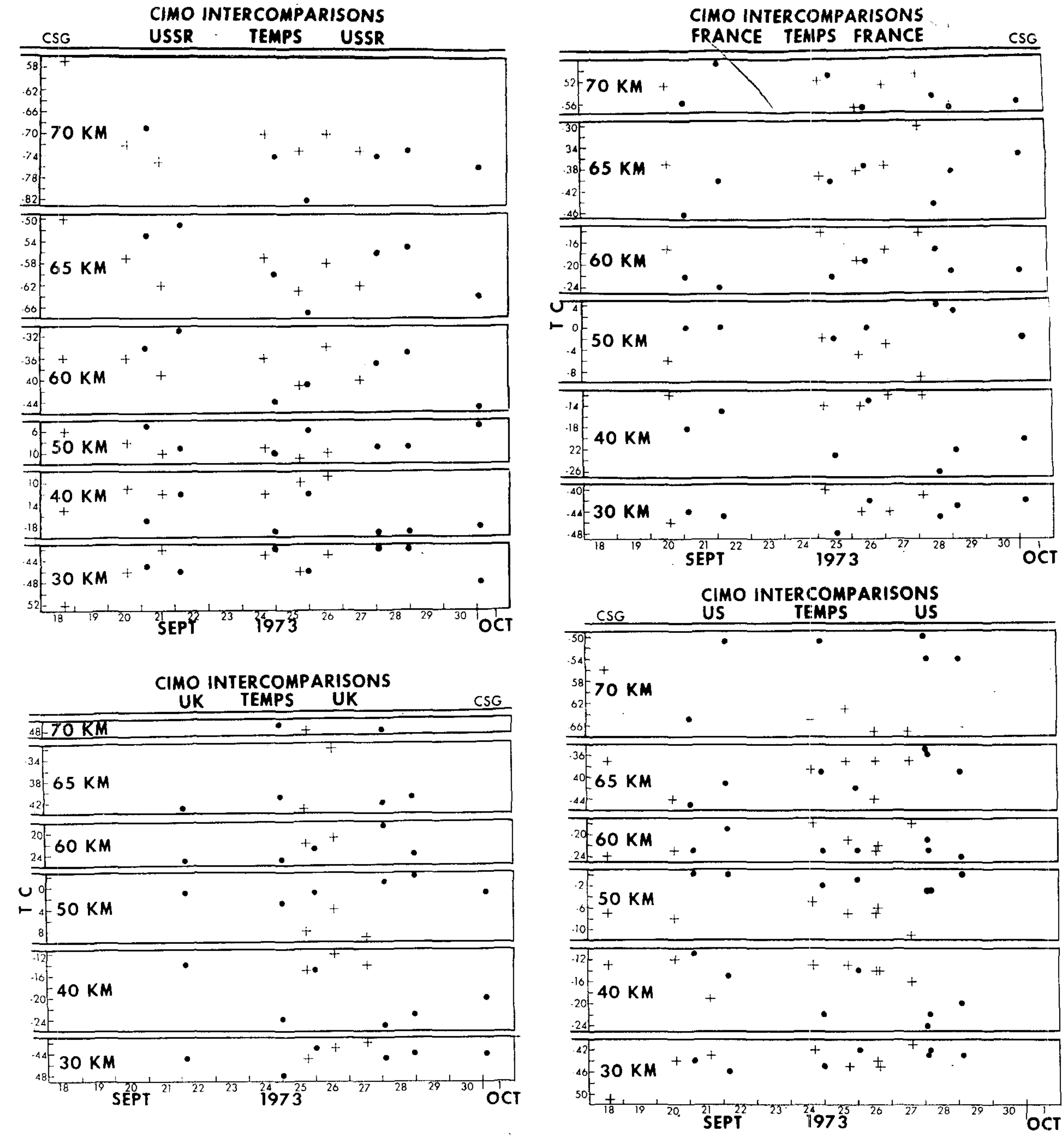

FIG. 8. Temperatures (°C) measured at 30, 40, 50, 60, 65 and 70 km for the CSG comparisons. Daytime observations are plotted with plus signs and nighttime observations with filled circles.

diurnal temperature changes. The theoretical 12 h temperature changes from noon to midnight, interpolated from Lindzen's (1967) diurnal variation calculations for the equinox at the Equator, are also indicated in Fig. 9, but at 2 km intervals. Between about 34 and 60 km there is substantial agreement between the sense of the measured and theoretical noon-midnight differences. The agreement is particularly evident around 50 km, where both theory and average temperature differences indicate noon temperatures to be lower than midnight temperatures by approximately the same amount. Also, good qualitative agreement is shown between 34 to 45 km, where positive noon-midnight temperature differences are indicated. At other levels the agreement is less clear.

We emphasize that only a very limited glimpse of the diurnal variation above CSG is possible from this set of data. The number of reports and their timing (9–15 h differences) do not allow any definitive comparison of measurement with diurnal theory. Therefore a comprehensive statistical evaluation of these interesting results was felt to be not warranted. We merely point out the overall reasonable agreement between theory and measurements of the various instruments. These results lead to significantly greater confidence in the internal consistency of temperature measurements at these levels.

5. Conclusions

The results obtained from the CIMO comparison tests have been extremely useful in evaluating the compatibility of meteorological rocketsonde data being gathered by various countries. Without such tests, differences in the data could be attributed to either measurement errors or real meteorological differences. Tests for other types of *in-situ* sensors as well as satellite remote sensors have also been accomplished (Miller and Finger, 1972). Based upon tests of these kinds we may attempt to reconcile biases among the measurements and to interpret the meteorological significance of the resulting data.

For use in meteorological analysis, adjustment factors (Table 3) have been developed to make the reported rocketsonde temperature data more compatible. The effect of these adjustments is to raise the temperatures reported by the U. S. S. R. system and lower those of the French system relative to U. S. measurements. Adjustments were not found necessary for data reported from Japan and the U. K. The values in Table 3 were derived with operational aspects in mind, such as whether observations are normally taken during daylight or darkness hours. Furthermore, the adjustments assume that the mean differences found at CSG and Wallops are representative of all conditions throughout the world. It should be added that if temperature differences are in reality a function of atmospheric temperature, comparisons would have to be made at many locations and atmospheric conditions to obtain adjustments valid for those conditions.

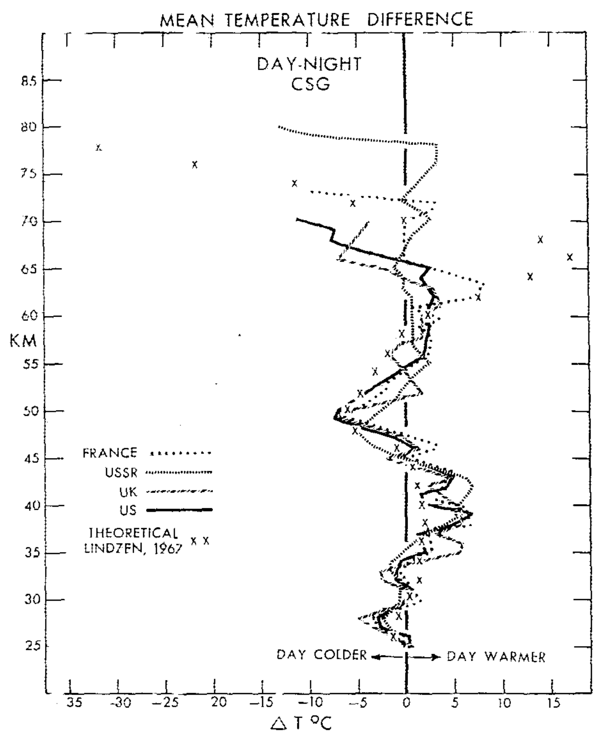

Fig. 9. Mean of the temperature differences between day and night temperature measurements. Theoretical noon minus midnight differences are shown by X's.

Table 3. Adjustments (°C) to U.S.S.R. and French reported temperatures considered necessary to achieve compatibility to U.S. values, assuming standard corrections have already been applied to all measurements.

	U.S.S.R.	France
70	+18	−10
65	+18	− 5
60	+15	− 4
55	+ 8	− 3
50	+ 7	− 2
45	+ 3	− 1
40	+ 1	0

No determination has been made here of the absolute validity of any set of measurements. There is as yet no standard for temperature measurement at these high levels. Therefore the best that can be attained is compatibility among the measurements. Each user of the data may choose the base level to which he will adjust all other data. We have chosen U. S. corrected measurements as this base. The comparisons accomplished to date represent only a first stage in the development of fully compatible high-altitude meteorological data.

Acknowledgments. This work was performed under partial support from the National Aeronautics and Space Administration under its EXAMETNET program. Partial support was also provided by the Naval Air Systems Command.

Many special efforts were put forth by members of Wallops Flight Center and the Guiana Space Center in order to meet the stringent schedules and to solve the operational problems which arose during these experiments.

REFERENCES

Almond, R., 1965: Techniques of temperature and wind sounding with the SKUA meteorological rocket. *Meteor. Mag.*, **94**, 327–331.

Izakov, M. N., A. Kokin and S. P. Tetrox, 1967: Methods of measuring pressure and temperature in meteorological rocket soundings. *Meteor. Gidrol.*, **12**, 70–86.

Krumins, M. V., and W. C. Lyons, 1972: Corrections for the upper stratosphere temperatures using a thin film loop mount. NOLTR 72-152, Naval Ordinance Laboratory, White Oak, Silver Spring, Md.

Lindzen, R. S., 1967: Thermally driven diurnal tide in the atmosphere. *Quart. J. Roy. Meteor. Soc.*, **93**, 18–42.

Mason, B. D., and J. Acres, 1972: Temperature corrections for the SKUA rocketsonde temperature sensor. *Meteor. Mag.*, **101**, 118–124.

Miller, A. J., and F. G. Finger, 1972: Results of a rocket-Nimbus sounder comparison experiment. NASA CR-62081, National Aeronautics and Space Administration, Wallops Station, Wallops Island, Va.

NASA, 1972: Meteorological rocket complex M-100 used for atmospheric sounding in the U.S.S.R. NASA Tech. Transl. F-14205. [Translation of unpublished report issued by U.S.S.R. Hydrometeorological Service, 1971.]

Tamaki, F., T. Nomura and N. Arizumi, 1965: MT-135 meteorological sounding rocket. SES Record 0001, Institute of Space and Aeronautical Science, University of Tokyo, and Japan Meteorological Agency, Tokyo.

United States, 1973: Rocketsonde observations. Federal Meteorological Handbook No. 10, Superintendent of Documents, U.S. Government Printing Office, Washington, D. C.

Villain, J., and B. Loitiere, 1972: Measure du vent de la temperature de la haute atmosphere. Establissement d'Études et de Recherches Meteorologiques, Paris.

Yata, A., 1970: Correction for the temperature data obtained by MT-135 system. *Geophys. Mag.*, **35**, 99–121.