Diurnal Variation of Temperature in the Upper Stratosphere as Indicated by a Meteorological Rocket Experiment

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ABSTRACT

Fourteen HASP and two ARCAS rockets, carrying WOX-1A and Arcasonde 1A instrumentation, respectively, were launched at Wallops Island during a 39-hr period in September 1965 to gain information regarding 1) the daily variation of temperature and wind within the 30- to 50-km layer, and 2) the compatibility between temperatures measured nearly simultaneously by the rocketsondes and by supporting balloon-borne radiosondes. Analysis of the observed rocketsonde temperatures indicates a diurnal variation ranging from about 3C at 30 km to 9C at 48 km. Marked differences in the temperatures measured by rocketsondes launched prior and subsequent to sunrise and sunset suggest that a portion of the variation may not be real, but is possibly a function of instrumental error. Support for this inference is provided by computations utilizing the rocketsonde winds as an independent means of determining the diurnal temperature wave. The results yield an amplitude about half that of the observed variation in the 35- to 45-km layer.

Temperatures obtained from several rockets launched within a short time interval disclose that the HASP (WOX-1A) system is capable of reproducing a given temperature profile with relatively small random error. In addition, ARCAS (Arcasonde 1A) measurements appear compatible with those of the HASP. However, a definite discrepancy was found to exist between rocketsonde temperatures and those reported by the supporting rawinsonde observations. Additional experiments are suggested as a means of determining the errors inherent in measurement of temperature by the various systems.

1. Introduction

During early September 1965, an experiment was carried out at Wallops Island, Va., to gather upper-stratospheric information regarding 1) the daily variation of temperature and wind, and 2) the compatibility between rocketsonde and radiosonde temperature measurements. Information of this nature is essential to effective utilization of the rapidly increasing quantity of high-level data. Many investigations have been hampered by the large and all too frequent discrepancies between temperatures measured nearly simultaneously by the rawinsonde and rocketsonde systems, as well as between those obtained at the higher levels by the rocketsonde system at different times of day. An excellent discussion of the uncertainties inherent in such data has been given by Belmont *et al.* (1964).

The experiment represented the first series of scheduled rocket launchings within the Experimental Inter-American Meteorological Rocket Network (EXAMETNET). This new international network, with stations presently located at Chamical, Argentina, Natal, Brazil, and Wallops Island, was organized as a cooperative effort among Argentina, Brazil and the United States (National Aeronautics and Space Administration) to facilitate studies of atmospheric structure and behavior in both the Northern and Southern Hemispheres. Network soundings will employ rockets similar to those launched during the September series. Participants in the experiment included representatives from Argentina and Brazil, and National Aeronautics and Space Administration personnel from Langley Research Center and Wallops Station. The Naval Ordnance Laboratory and Environmental Science Services Administration were also represented.

2. Plan of experiment

Any experiment designed for a determination of the diurnal temperature and wind variation, ideally, should include frequent observations during a 24-hr period. In addition, the 24-hr series should be repeated a sufficient number of times to achieve statistically significant results. However, the relatively high cost of rocketsonde observations generally precludes such an elaborate procedure. Therefore, the experiment was devised to extract as much pertinent information as possible from a necessarily limited number of rocket soundings.

Fourteen HASP III rockets, equipped with JUDI motors and WOX-1A rocketsonde payloads (Parker, 1965) were made available by the Naval Ordnance Laboratory and NASA, Wallops Station. An enlarged view of the temperature sensing portion of the WOX–1A is shown in Fig. 1a. A nominally 14-mil bead thermistor, utilized in this instrument, is mounted within the cutout portion of a flat plastic support measuring less than 1/2 inch in width and about 1/16 inch in thickness. The section directly above and below the bead is

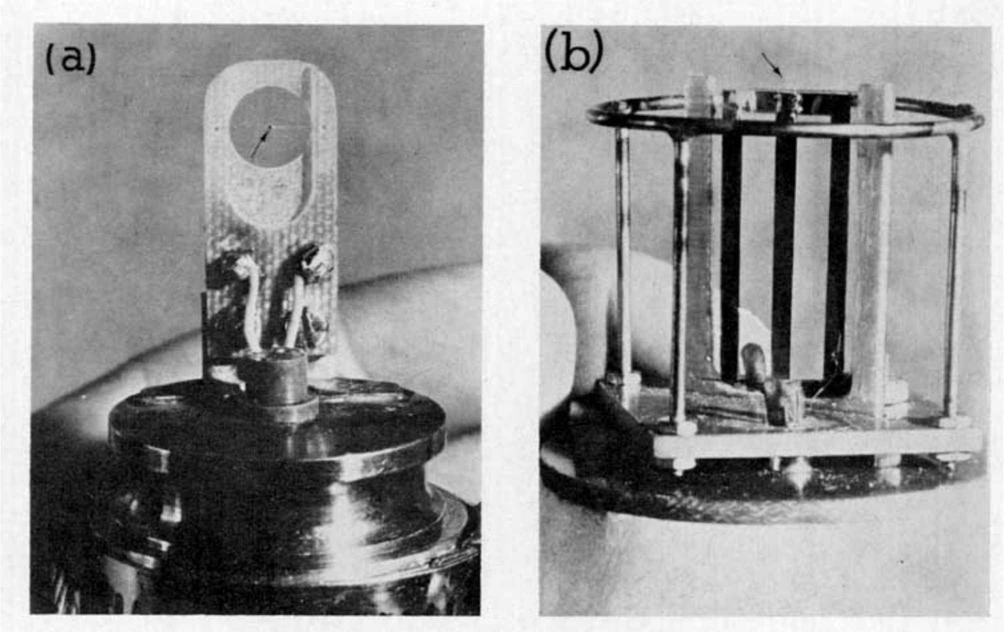

FIG. 1. Temperature-sensing portions of rocketsonde instruments, with bead thermistors located by arrows: (a) WOX-1A; (b) Arcasonde 1A.

considerably thinner than the latter value. In addition, two ARCAS rockets (Jenkins, 1965) containing Arcasonde 1A instrumentation (Daniel, 1965) were allocated to the experiment by the NASA Langley Research Center. The thermistor mounting, shown in Fig. 1b, consists of a 1-mil mylar sheet attached to phenolic posts. Aluminum strips bonded to the mylar serve both as electrical leads between the 10-mil bead and the telemetry circuits, and as an rf trap to prevent heating of the thermistor. The entire assembly is normally protected by a removable thermistor guard, which was left in place on the instruments employed for this experiment.

Models of stratospheric temperature structure (Johnson, 1953; Pressman, 1955; Gebhart, 1965) suggest that the true diurnal wave is quasi-sinusoidal in shape and attains a maximum and minimum at approximately sunset and sunrise, respectively. Results from studies utilizing large samples of rawinsonde data (Harris *et al.*, 1962; Finger *et al.*, 1965) support these models up to about 30 km. Therefore, if the diurnal oscillation above that level is to be estimated with the aid of only a few rocket observations, launch times near sunrise and sunset would appear to be appropriate. In addition, information regarding possible radiation errors in measured temperature may be obtained if pairs of observations can be scheduled immediately preceding and following both sunrise and sunset. The daylight-darkness differences provided by such measurements may be attributed to instrumental error, such as that due to the absorption of solar radiation by the thermistor or other instrument components.

The basic program of the experiment was to launch rockets as soon before and after sunset and sunrise as possible during a two-day period. While the soundings comprising the daylight-darkness pairs ideally should have been taken only minutes apart, operational considerations, such as provision for replacement launches in the event of failures, resulted in separations of a few hours. Additional rockets were included in the program to measure temperature at noon and midnight. The diurnal wave, according to theory, has inflection points at approximately these times.

In order to obtain information on the repeatability of temperature measurements from the same type of instrument and the compatibility between reports from different types, several rockets were added to those already scheduled for launching before and after the first sunset. Launch times, altitudes of payload ejection, and observed temperature data for the entire series are presented in Table 1.

In accordance with the standard procedure for meteorological rocket operations, rawinsonde observations were planned to accompany most rocketsondes. Releases were scheduled, when feasible, so that the ascending radiosonde and descending rocketsonde would pass through the 30-km level at approximately the same time. All radiosonde instruments employed hypsometers for precision measurement of pressure. Scheduling of several special high-level balloons capable of attaining heights above 35 km provided an especially deep layer of overlap with the rocketsonde observations. Release times and temperature data for rawinsonde observations are also included in Table 1.

An experiment such as that described above may easily be contaminated by synoptic-scale weather changes. Hence, September, when the stratospheric circulation is weak and inactive, was selected as an ideal period in which to conduct the experiment. During the course of the series, the flow pattern at 10 mb over the eastern United States consisted of a nearly stationary ridge with very light winds. The ridge line itself was oriented east-west at about the latitude of Wallops Island.

3. Analysis of temperature variations

All rocket soundings from the series were reduced by personnel of Wallops Station. In accordance with regular operating procedure, no temperature corrections were applied to the data obtained by either the WOX-1A or Arcasonde 1A. An initial inspection of the data revealed that, regardless of time of day, unreasonably high temperatures were reported immediately after payload ejection. Such unrealistic temperature readings are believed to be due to retention by the instrument of a portion of the aerodynamic heating produced within the nosecone during ascent. In most cases, this heat appeared to be sufficiently dissipated after the payload had descended 4 km from ejection altitude. Even though in some soundings temperature values at levels closer to ejection seemed reasonable, all data from this top 4-km layer were excluded from analysis.

In the first analysis effort, temperature data for specific levels were used in various computations. However, it became evident that small-scale features within the soundings were accounting for a disproportionate amount of the total temperature variation. Many such features may be real, but for the purposes of the experiment served only to raise the noise level. In order to filter out this "noise" and yet preserve the essential character of the profiles, mean temperatures were computed for 4-km layers at 2-km intervals, and assigned to the mid-points of the layers. The resulting temperatures were utilized to construct the curves shown in Fig. 2. For this representation, all values obtained during the 39-hr period were compressed into a single 24-hr interval.

Temperature data plotted in Fig. 2 for the various levels clearly exhibit a diurnal trend with a maximum during the day and a minimum at night. In a few cases, however, rather large dispersion of data obtained from closely spaced observations obscures this trend. This dispersion is most noticeable at the 34-km level. Analysis of observed data, as shown by the curves, was performed with the aid of the assumption that the wave peaks at sunset and reaches a minimum at sunrise, and with the constraint of vertical continuity between levels. Generally, the employment of this latter restriction yielded results consistent with the observed data. Although the observations seem to support

TABLE 1. Observed rocketsonde and rawinsonde temperature data (°C), Wallops Island, 8–10 September 1965.

Rocketsonde

	8 September							9 September						10 September		
Time (EST)	1645	1735	1807	1947	2026	2041	2125	0001	0305	0701	1148	1734	2015	0000	0300	0738
Rocket type	HASP	ARCAS	HASP	HASP	ARCAS	HASP	HASP	HASP	HASP	HASP	HASP	HASP	HASP	HASP	HASP	HASP
Payload ejection (km)	53.9	53.3	56.1	52.8	51.8	49.7	53.3	53.3	54.7	54.2	51.8	56.2	52.5	51.6	53.2	53.5
Height (km)			sunset 1900						sunrise 0500			sunset 1900			sunrise 0500	
52			6									2				
50			4						— 4			2				
48		5	— 1				— 4	— 3	— 8	1		— 2	1	— 6	— 9	
46	— 1	— 2	msg	— 6	— 5		— 7	— 5	—10	— 5		1	— 4	— 7	—11	— 6
44	— 2	— 1	msg	— 9	— 9	— 8	—10	—13	—12	— 6	— 6	— 4	—11	— 8	—16	— 5
42	— 8	— 7	msg	—15	—15	—10	—11	—16	—11	—12	— 9	—10	—13	—12	—16	—15
40	—17	—15	msg	—19	—22	—19	—17	—18	—19	—16	—11	—18	—22	—20	—21	—13
38	—18	—19	msg	—26	—24	—25	—24	—25	—26	—24	—22	—23	—17	—25	—23	—20
36	—26	—24	msg	—28	—29	—28	—31	—31	—28	—28	—27	—24	—31	—28	—29	—29
34	—36	—35	—25	—33	—32	—37	—32	—34	—36	—32	—29	—29	—36	—35	—34	—29
32	—37	—40	—38	—40	—41	—40	—39	—37	—39	—37	—38	—36	—37	msg	—36	—39
30	—40		—41	—45	—46	—44	—43	—42	—40	—43	—41	—41	—41	msg	—41	—44
28	—43		—42	—46	—49	—48	—46	—48	—46	—44	—47	—44	—47	msg	—45	—42
26	—45		—47	—49	—51	—50	—50	—52	—48	—49	—48	—48	—47	msg	—52	—48
24	—50		—50	—52	—53	—52	—53	—50	—53	—50	—52	—51	—53	msg	—54	—53
22	—55		—54	—55	—55	—55	—54	—53	—55	—55	—54	—56	—56	—57	—56	—55
20	—56		—58	—57		—56	—56	—56	—58	—59	—57		—58	—60	—60	—61

Rawinsonde

Time (EST)	1515	2136	0340	0605	1006	1531	2300	0205	0545
Height (km)									
40						—26			—21
38	—31			—32		—28			—24
36	—33			—29		—30	—35		—30
34	—38	—36		—32		—33	—38		—34
32	—38	—42	—42	—36		—37	—41		—42
30	—40	—45	—45	—41		—41	—44		—41
28	—46	—48	—46	—45	—46	—46	—48		—42
26	—48	—52	—50	—50	—47	—49	—51	—52	—48
24	—50	—54	—52	—50	—53	—52	—54	—54	—55
22	—53	—56	—56	—54	—54	—56	—57	—57	—55
20	—56	—57	—59	—59	—60	—59	—60	—60	—61

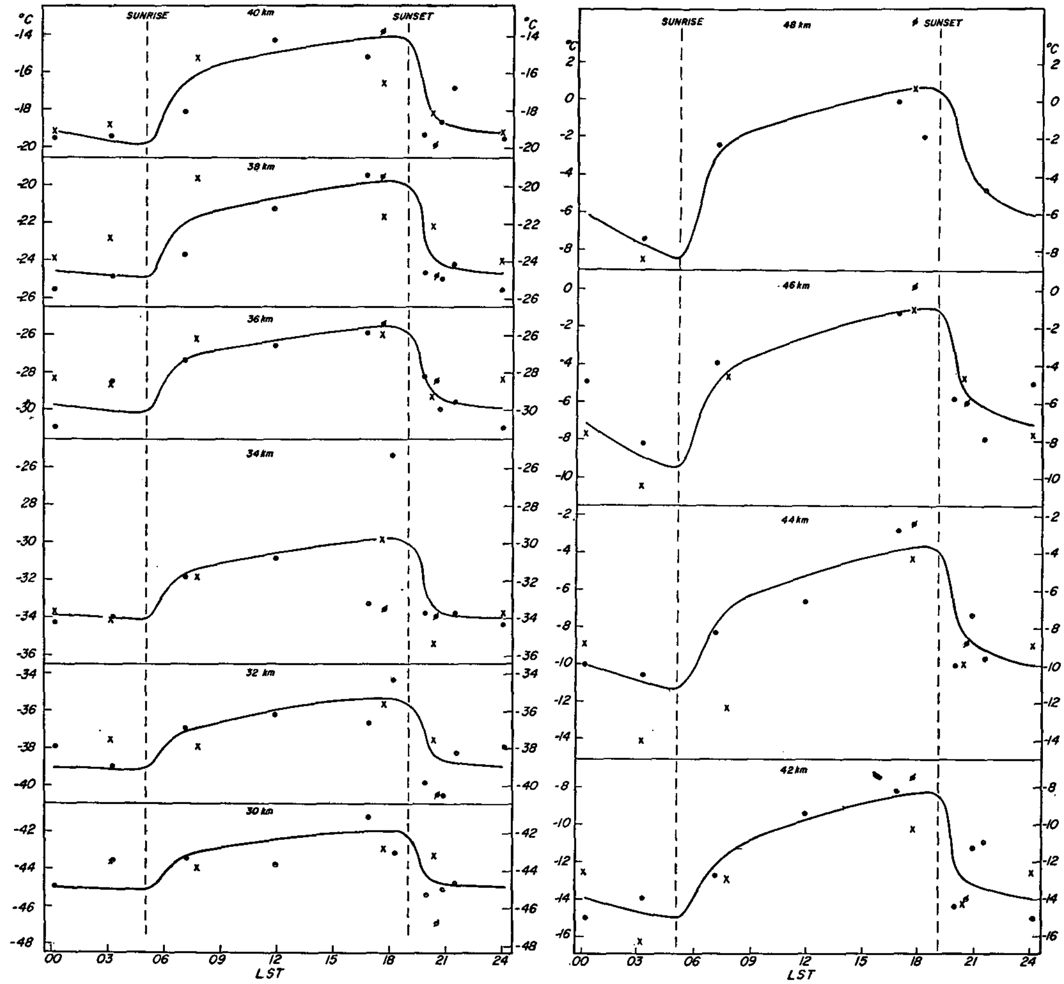

FIG. 2. Analyses of mean rocketsonde temperatures for 4-km layers. Observations taken during a 39-hr period have been compressed into a 24-hr interval. Dots, data obtained between 1600 EST 8 September and 1600 EST 9 September 1965; solidus through dots, ARCAS reports; crosses, data obtained between 1600 EST 9 September and 0800 EST 10 September.

placement of the maximum at sunset, it is realized that diurnal patterns with a peak somewhat before that time would not inordinately violate the data. A minimum at a time other than near sunrise does not appear probable.

The analyses (Fig. 2) indicate a daily temperature range varying from about 3C at 30 km to about 9C at 48 km. An investigation of the diurnal variation was conducted at White Sands Missile Range during the period 7-9 February 1964 (Beyers and Miers, 1965). Measured temperatures from this series of 13 rocket soundings (11 at 2-hr intervals), which utilized the White Sands Deltasonde instrument, indicated a variation of about twice the magnitude of that shown in Fig. 2. Cole and Nee (1965), in analyzing the White Sands data, conclude that a portion of the observed variation may be due to random variability and observational error.

Important as an influence in determining the wave shapes (Fig. 2) are the marked differences between temperature values measured in daylight prior to sunset, and those obtained in darkness after sunset. In general, the daylight temperatures are considerably higher than those of the darkness group. The differences can be seen to increase with height. It is noteworthy that although the observations comprising each of the groups are separated by an hour or more, no definite trend with time is evident within the groups themselves. That is, the sharp temperature change appears to take place between the groups, and within a very short time interval close to sunset. Since the data surrounding sunrise are separated by a larger time interval than those at sunset, the relative sharpness of the changes at that time cannot be established.

4. Diurnal and semi-diurnal variations of wind

Rocketsonde winds were utilized in an independent attempt to determine the phase and amplitude of the diurnal temperature variation. These winds were

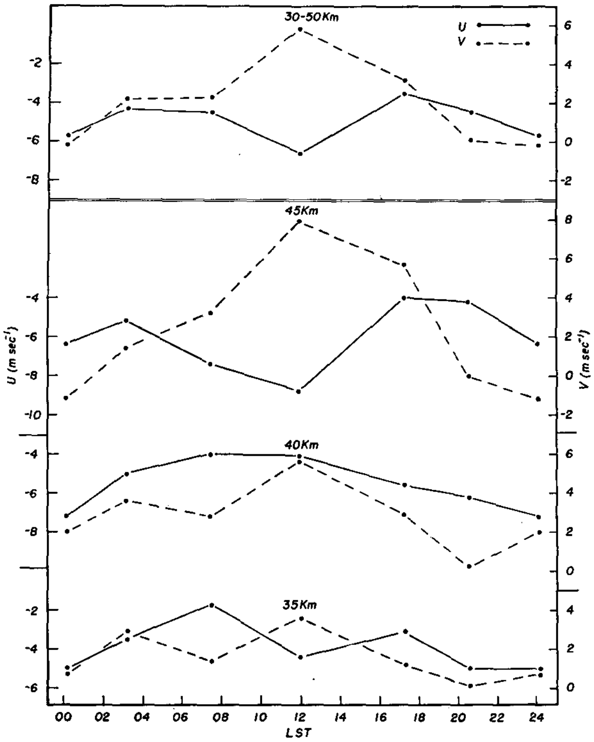

FIG. 3. Variation in 24-hr period of eastward *U* and northward *V* wind components averaged in three 10-km layers, surrounding the levels indicated. Means for 20-km layer (30 to 50 km) are also included.

measured by radar tracking of a 6-ft square parachute of metalized silk deployed by the HASP, and a 15-ft diameter partially metalized parachute carried aloft by the ARCAS. As stated previously, very light winds prevailed over Wallops Island during the period of the experiment. While extremely accurate FPQ-6 and FPS-16 radars were employed, it is nevertheless possible that in some cases the measured wind changes were smaller than the limits of radar tracking capability [see Belmont *et al.* (1964)].

A total of fifteen rocketsonde wind profiles was obtained from the series. However, two of the observations, one obtained by HASP and one by ARCAS, were usable only in the higher levels. Wind components were determined by averaging the radar position data, recorded at 5-sec intervals, in 2-km layers. Initially, these components were smoothed by the same 4-km layer averaging that had been applied to the temperatures. However, it was evident that small-scale perturbations were causing the values to fluctuate in an erratic manner from level to level. In order to filter out this "noise," the thickness of the layer employed in averaging was increased to 10 km. Mean values were also computed for the entire 30–50 km layer.

Wind components were compressed, as were temperatures, into a single 24-hr period. In addition, observations separated by an hour or less were combined. The resulting composite eastward *U* and north-

TABLE 2. Amplitude and time of maximum of the first and second harmonics of the observed wind variation.

Station and period of record	Level (km)	U(1) a_1(3)	t_1(4)	a_2(5)	t_2(6)	V(2) a_1	t_1	a_2	t_2
Wallops Island 8–10 Sep 65	45	2.0	2100	1.5	0535	4.2	1220	0.7	0405
	40	1.5	0950	0.4	0600	1.8	1005	1.3	0145
	35	1.0	0845	1.2	0555	1.2	0925	1.1	0150
	(7) 40	0.5	2115	1.4	0550	2.5	1135	0.7	0225
Lajes Apr 56–Mar 58	28.5	0.3	2035	0.9	0305	0.7	1220	0.6	0010
	23.9	0.2	1610	0.7	0350	0.2	1330	0.6	0040
White Sands 7–9 Feb 64	50	3.1	2155	1.6	0455	1.9	0955	3.3	0225
	45	13.2	2335	5.1	0430	10.0	1425	2.1	0320
	40	5.9	0455	2.3	0510	2.3	2305	0.9	0610
	35	4.7	1040	2.5	0340	2.5	0705	0.8	0140
	30	0.2	0805	0.8	0300	0.3	1555	1.7	0235
White Sands 21–22 Nov 64	50	5.7	2005	1.4	0305	8.4	1035	1.6	0230
	45	5.5	1140	3.0	0340	5.0	1340	5.2	0210
	40	0.5	1405	2.0	0520	1.3	2155	1.7	0330
	35	2.2	1530	1.0	0740	5.1	1050	1.7	0240
	30	0.7	0355	1.2	0330	1.8	1950	0.7	0200
Eglin 9–10 May 61	50	3.4	1520	1.9	0805	7.7	1110	2.0	0130
	45	6.7	1730	1.4	0535	7.8	1310	2.4	0435
	40	1.9	0230	2.5	0240	1.3	0835	1.9	0125
	35	0.6	2000	0.8	0605	1.9	1030	1.9	0325
	30	2.1	1040	0.9	0325	1.4	0805	0.8	1140

(1) Eastward component.
(2) Northward component.
(3) Amplitude of first harmonic, m sec^{-1}.
(4) Time of maximum of first harmonic, local standard time.
(5) Amplitude of second harmonic, m sec^{-1}.
(6) Time of maximum of second harmonic, local standard time.
(7) Based on 30–50 km layer mean.

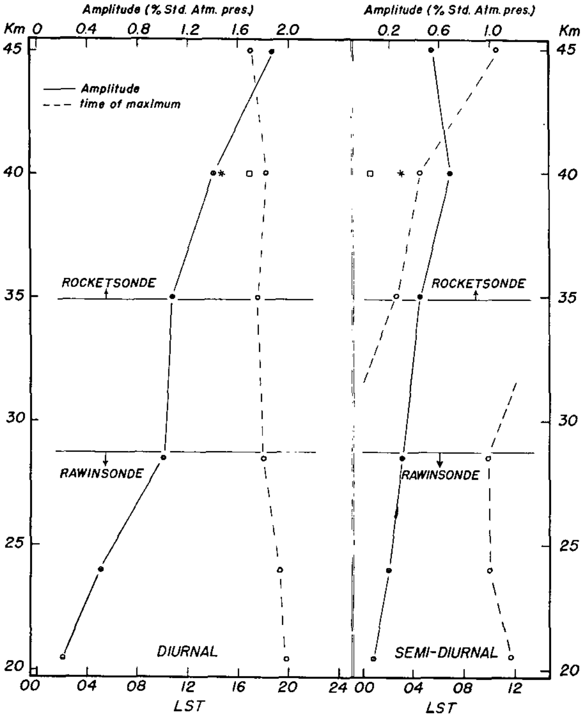

FIG. 4. Amplitude (per cent of standard atmosphere pressure) and time of maximum of diurnal and semi-diurnal pressure oscillations, as determined from harmonic coefficients of the wind variations. Amplitude and time of maximum, computed from mean winds for the 30–50 km layer, are denoted by asterisks and squares, respectively. Values in rawinsonde region are for Lajes.

ward *V* wind components are presented in Fig. 3. An increase in the amplitude of the variation with height is evident. Although inspection of the data revealed that the largest variability occurred above 45 km, the number of observations at the highest levels was inadequate for computation of a 45–55 km layer average.

A harmonic analysis was performed on the layer-mean wind components. The resulting phases and amplitudes are listed in Table 2, together with values previously computed from the large sample of rawinsonde data for Lajes, Azores (Harris *et al.*, 1962), which is at nearly the same latitude as Wallops Island. Amplitudes of both the diurnal and semi-diurnal variations exhibit a fairly smooth transition between rawinsonde and rocketsonde levels. The diurnal amplitude increases almost linearly with height, while that of the semi-diurnal tends to increase only slightly. Because of the 10-km layer averaging of observed wind components, computed anplitudes for the higher levels represent a slight underestimate. Results of harmonic analyses of winds measured during other short-period rocketsonde series conducted at White Sands Missile Range, New Mexico and Eglin Air Force Base, Florida (Miers, 1965) are also listed in Table 2.

5. Pressure and temperature variations as indicated by the observed winds

The phase and amplitude of the pressure variation may be computed from the harmonic coefficients for the wind components with the aid of a model based on the linearized equations of motion for frictionless flow and the assumption that the diurnal and semi-diurnal oscillations are simple progressive waves (Harris, 1959). Resulting pressure-wave amplitudes and times of maximum are shown in the upper portion of Fig. 4, with information previously computed for Lajes given in the lower part. Parameters of the diurnal pressure variation obtained from the two studies are most striking in their consistency. An almost linear increase of amplitude, and near-constancy of phase, with height are evident. The time of the diurnal pressure maximum is in early evening. Since the pressure and temperature maxima should be nearly coincident, results of the wind analysis tend to support the placement of the temperature maximum near sunset as shown in Fig. 2.

The computed amplitudes for the semi-diurnal pressure wave are considerably smaller than those for

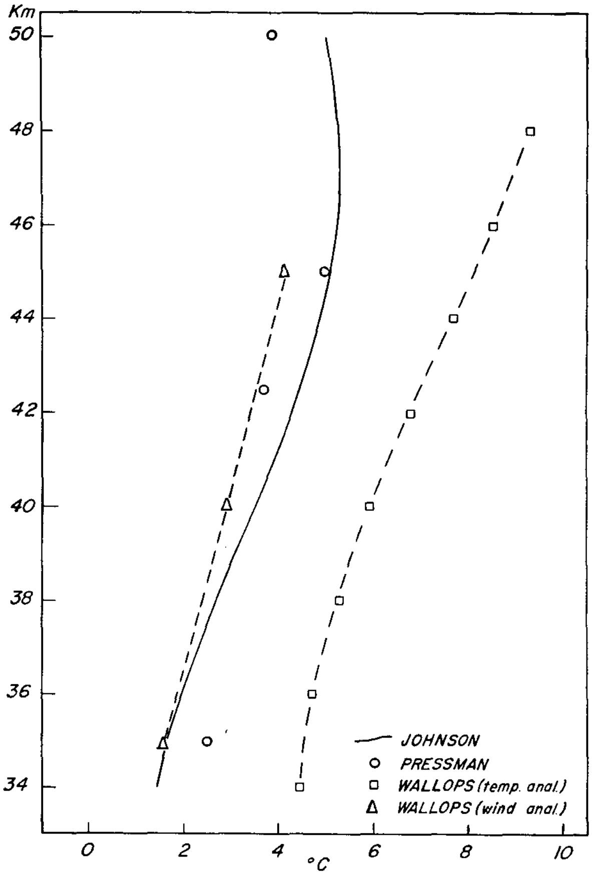

FIG. 5. Diurnal temperature range (maximum minus minimum) from analyzed curves in Fig. 2. Values derived from wind analysis are shown along with theoretical estimates of Johnson (1953) and Pressman (1955).

the diurnal, and only a low degree of confidence can be placed in the phase angles. However, the rocketsonde wind data do suggest that the time of maximum rotates clockwise with increasing height. Somewhat less than a full cycle is indicated between 35 and 45 km.

Amplitudes of the diurnal pressure wave at 35, 40 and 45 km, computed from the layer-mean winds, were combined with pressure values extracted from the U. S. Standard Atmosphere (COESA, 1962) to obtain diurnal maximum and minimum pressures for those levels. The latter quantities were employed in the barometric equation to determine maximum and minimum mean temperatures for the layers 35–40, 35–45 and 40–45 km, which in turn were utilized for the computation of diurnal temperature ranges at 35, 40 and 45 km. Results of these computations are shown in Fig. 5 along with the temperature ranges derived by Johnson (1953) and Pressman (1955). As mentioned previously, the computed amplitudes of the diurnal wind oscillation for the highest level are conservative because of the deep layer employed in smoothing. Therefore, the derived pressure- and temperature-wave amplitudes may also represent a slight underestimate of the real variations. Also included in the figure are the ranges determined from the analysis of the Wallops Island temperature data in Fig. 2.

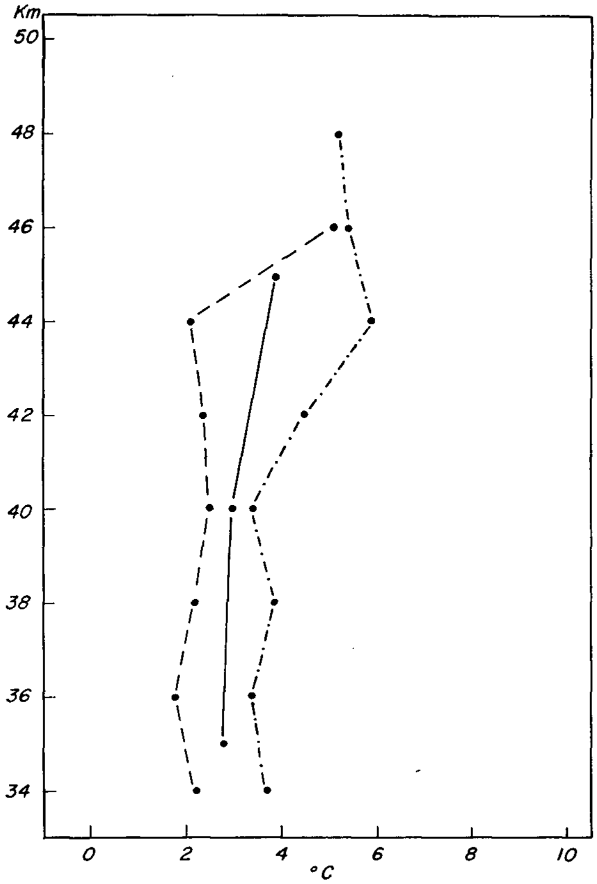

FIG. 6. Differences between diurnal ranges from temperature analysis and those derived from wind analysis (solid line); average daylight-darkness differences from observed temperature data at sunrise (dashed line) and sunset (dash-dot line).

A close correspondence is evident (Fig. 5) between the theoretical values and those obtained from the wind analysis. While the profile of observed temperature range is generally consistent in shape with that derived from the winds, the difference in magnitude varies from about 2.5C at 35 km to approximately 4C at 45 km (Fig. 6). Profiles of the mean daylight-darkness differences derived from the observed temperature data are also shown in Fig. 6. These profiles were obtained by grouping before- and after-sunrise pairs, and before- and after-sunset pairs. Darkness temperatures were then subtracted from daylight values in each pair. A tendency for the sunset differences to be higher than those at sunrise is most noticeable. The two profiles also tend to bracket the central profile, which indicates the differences between the diurnal ranges obtained from the temperature and wind analyses. In fact, this latter profile is approximately equal to the over-all mean of the observed day-night differences.

The sharp changes in the measured temperatures near sunset (Fig. 2), coupled with the differences shown in Fig. 6, suggest the existence of instrumental error that is radiational in nature. Theoretical and laboratory studies by Ney *et al.* (1961) and others have indicated that aluminized beads of approximately 10-mil diameter should exhibit insignificant short-wave and infrared errors up to at least 50 km. However, it is possible that the discrepancies in measured temperatures are due to errors induced by radiation from exposed components of the rocketsonde instrument.

6. Comparison of rocketsonde and radiosonde temperature measurements

As stated previously, five HASP and two ARCAS rockets were launched in as rapid succession as possible during the first sunset interval (see Table 1). The purpose of this sequence was to assess the repeatability of temperature measurements from the same type of instrument and the compatibility between reports from different types. Complete temperature profiles obtained from the three rocket observations before sunset (Fig. 7a) are generally quite similar, as are those from the four after sunset (Fig. 7b). An exception is found at the very highest levels, where the large discrepancies illustrate the need for extreme caution in the evaluation of temperatures measured near apogee. Another salient feature of the profiles is the appearance of small-scale changes, which in many cases seem to be real perturbations. These features are an indication of the resolution with which the rocketsonde can measure atmospheric structure.

The temperature profile from the first supporting rawinsonde observation, taken before sunset and entirely in daylight, can be compared in Fig. 7a with

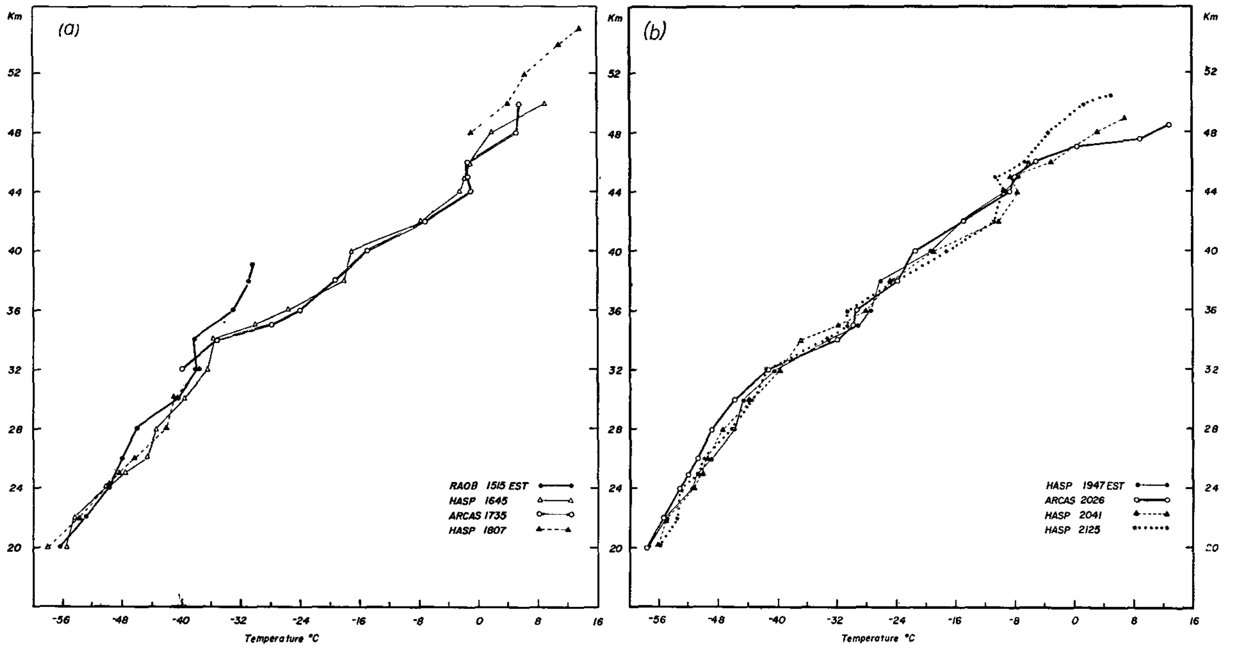

Fig. 7. Rocketsonde and rawinsonde temperature profiles for 8 September 1965: (a) before sunset, (b) after sunset.

the values obtained from the associated rocketsonde reports. General agreement between measurements by the two systems is evident up to about 32 km. In this case, the balloon-borne radiosonde, released at 1515 EST, passed that level at about the same time as the descending parachute carrying the HASP rocketsonde launched at 1645 EST. Above 32 km, the temperature profiles diverge markedly, with the radiosonde indicating lower temperatures than the rocketsonde. At 39 km, the maximum altitude attained by the radiosonde, the magnitude of the difference is about 13C. Four additional supporting rawinsondes that reached heights in excess of 35 km also indicated low values in comparison with the rocketsonde temperatures obtained at nearly the same time, regardless of whether the observations took place in darkness or in daylight.

Additional evidence of incompatibility between temperature values reported by radiosondes and by the HASP and ARCAS rocketsondes is presented in Fig. 8. Data utilized for the radiosonde-rocketsonde temperature differences included reports from the Wallops series in addition to those of other stations for the period January 1964 through February 1965, extracted from *Data Reports of the Meteorological Rocket Network Firings* (MRNC, 1965). Data selected are those to which no temperature corrections have been applied. To

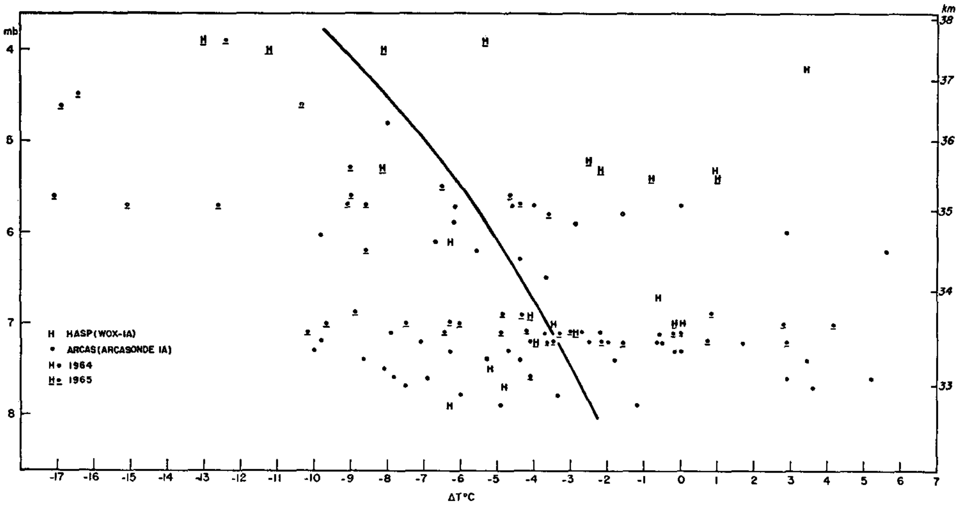

Fig. 8. Differences between rocketsonde and rawinsonde temperatures measured at nearly the same time and level (rawinsonde minus rocketsonde). Curve is result of least-squares analysis of ΔT versus $\log P$.

obtain the differences, rocketsonde temperatures were interpolated linearly for each pressure level at which supporting radiosonde values were reported. Differences were computed only when both rocketsonde and balloon reached the indicated level in daylight and within six hours of each other.

Quite apparent in Fig. 8 is the large dispersion in the plotted differences. A portion of this random scatter may be accounted for by possible real temperature changes, both synoptic and tidal, that occurred during the time interval between observations. The difference between the positions in space of the rocketsonde and radiosonde instruments could also be a contributing factor. An additional and important consideration is the type of radiosonde instrument in use at each station. Many ascents undoubtedly employed hypsometer sondes, with negligible pressure error. However, the uncertainty in pressure measurement by the conventional aneroid element at very high latitudes can lead to error in reported temperature.

In spite of the large dispersion, the differences, which are predominantly negative, exhibit a tendency to increase with height. A least-squares analysis of ΔT versus $\log P$ (see curve, Fig. 8) confirms this feature. The systematic increase in differences may be dependent in part on the short-wave and infrared radiation errors inherent in the white-coated, externally-mounted rod thermistor used with the regular balloon-borne radiosonde instrument (Ney *et al.*, 1961; Finger *et al.*,1964). In the stratosphere, during daylight hours, solar heating and infrared cooling affect the thermistor simultaneously. From a series of laboratory and field experiments, Ney concluded that above 30 km, the infrared cooling of the rod thermistor increases more rapidly with height than the heating induced by solar radiation. As a result, measured temperatures at 45 km could be as much as 13C too low. It has also been pointed out that the magnitude of this type of error may be influenced significantly by the temperature of underlying clouds or surface (Armstrong, 1965).

It may be presumptuous to suggest that the radiosonde-rocketsonde temperature differences are entirely a function of the infrared error of the radiosonde thermistor. Aside from the effects of solar radiation on the instruments a portion of the discrepancy may arise from the in-flight behavior of a given type of sonde. For example, the response time of the radiosonde rod thermistor at 40 km is about 30 times longer than that of the rocketsonde bead. Since the environmental temperature normally increases with height at that level, the lag of the instruments will cause the radiosonde to report lower values. However, in the presence of a typical inversion, of perhaps 3C km^{-1}, the difference due to lag is only about 1C. The problem of overall rocketsonde temperature-measurement accuracy has been studied theoretically by Wagner (1964). His study, based on the Deltasonde, indicated that all sources of rocketsonde error, including radiation, self-heating, lead-wire conduction, aerodynamic heating and lag, should cause measured temperatures to be only slightly higher than ambient below about 50 km. A considerable amount of further research, including experimental work, is required before the problem of radiosonde-rocketsonde differences can be resolved.

7. Conclusions

A limited sample of rocketsonde temperature and wind data, gathered by the HASP (WOX-1A) and ARCAS (Arcasonde 1A) system during the Wallops Island experiment, has provided an indication of the diurnal variation of temperature and wind in the layer from 30 to 50 km. Analysis of observed temperature discloses a diurnal range increasing from about 3C at 30 km to 9C at 48 km. These values, at all levels, are larger than predicted by theory. In addition, at 30 km the range is larger than that obtained from studies utilizing a large quantity of rawinsonde data.

A method utilizing the rocketsonde wind observations was applied as an independent means of determining the phase and amplitude of the diurnal temperature wave in the 35–45 km layer. The results of the computations are inconsistent with those obtained from the observed temperatures, and indicate a diurnal variation quite similar to that predicted by theory.

Comparison of rocketsonde temperature data from three HASP launches within a relatively brief time interval has shown that system to be capable of a high degree of repeatability. In addition, the small sample of Arcasonde 1A data obtained from the experiment appears to be quite compatible with the WOX-1A reports. However, differences increasing with height were noted between temperatures measured by the rocketsondes and supporting rawinsonde observations, with the latter values lower in all cases. Analysis of radiosonde-rocketsonde differences based on a large sample of Meteorological Rocket Network data confirms this tendency.

It is proposed that the discrepancy between the diurnal temperature variations obtained independently from the temperature and wind analyses is attributable to radiational error of the rocketsonde instrument. Rapid changes in the observed temperatures near sunset and sunrise tend to confirm this inference. However, there is little doubt that carefully planned experiments are needed to provide more definitive information. One such test might consist of a series of paired rocketsonde observations, minutes apart, in darkness and daylight very close to the times of sunrise and sunset. The time between observations in each pair has to be kept short in order to minimize the influence of the real diurnal temperature variation, and the number of pairs must be large enough to assure statistical significance in the presence of random errors and synoptic-scale changes. If this experiment results in the detection of a radiational error, a correction system appropriate to the particular instrument employed may be devised. The true diurnal variation could then be determined by means of a series of corrected observations at regular intervals over a period of a few days.

Further experimentation is also necessary to determine representative values of the magnitude of the discrepancy between rocketsonde and radiosonde temperature measurements, and the proportions attributable to each instrument. The desired information might be obtained from a series of flights of modified balloon-borne radiosondes, each carrying two or more thermistors of different types. Simultaneous observations with rocketsondes similarly modified would permit additional comparisons with radiosondes at the higher levels.

The two experiments suggested above might be combined if the difficult operational problems, including the monitoring of transmissions from several radiosondes and rocketsondes in flight simultaneously, could be solved. Such tests would help to define proper correction systems for the various sensors. The availability of such corrections will allow both rocketsonde and rawinsonde observations to be utilized with a much higher degree of confidence.

Note. While this article was in review, Reed *et al.* (1966) presented in this Journal a simple global model of the diurnal tide, which encompassed the results of several previous theoretical and observational studies. The planning of the experiment described here, and the analysis methods employed in this study, are in accord with that model.

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