Observed Diurnal Oscillations of Pressure and Density in the Upper Stratosphere and Lower Mesosphere

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ABSTRACT

Two recent series of meteorological rocket measurements in the upper stratosphere and lower mesosphere conducted in the summer and fall of 1965 at White Sands Missile Range, New Mexico, indicate a significant diurnal oscillation of pressure and density in this region. The amplitude of observed pressure oscillations over an averaged layer from 52 to 58 km varied from 4–7 per cent with a mean value of 5 per cent, while the amplitude of density averaged through the same layer varied from 3–5 per cent with a mean of 3.5 per cent. Harmonic analyses of the heights of the 1.0-, 0.6- and 0.4-mb surfaces indicate maxima at approximately 1400 and 1200 hours (local time) for the summer and fall series, respectively. In the vicinity of 55 km the total range of the diurnal oscillations of pressure and density as evidenced by these data was found to be almost as large as the seasonal variability.

1. Introduction

In recent years the Meteorological Rocket Network (Webb *et al.*, 1962) has produced a fairly large volume of atmospheric data from the upper stratosphere and lower mesosphere, and because of operational complications, the vast majority of the measurements have been made in the daytime. There were occasional night firings, however, and upon inspection of these data, it became obvious that diurnal oscillations of the various atmospheric parameters were much greater than had been estimated previously, especially with regard to diurnal wind oscillations (Lenhard, 1963). In February 1964, a 24-hr series of meteorological rocket measurements was made at regular 2-hr intervals to investigate tidal motions in more detail (Miers, 1965) and also to investigate diurnal oscillations of temperature, pressure and density. Although the number of temperature measurements was considerably less than the number of wind observations during this series, the data were sufficient to reveal a significant diurnal temperature variation as reported by Beyers and Miers (1965). Since the temperature data were numerically restricted and since questions are often raised concerning the large corrections (Wagner, 1961, 1964) that were necessary with the instrumentation in use at the time, only a limited evaluation of pressure and density oscillations was made (Miers *et al.*, 1965). However, because of the good agreement with two subsequent series of measurements, the temperature, pressure and density oscillations in the stratopause region observed during the February 1964 series seem realistic.

The next two series, utilizing improved instrumentation, were conducted during 48-hr periods in the summer and fall of 1965 at White Sands Missile Range, to investigate diurnal variations in greater detail and in different seasons. The dates and times of these observations are listed in Table 1. In reporting on the wind and temperature for the summer series (30 June through 2 July), Beyers *et al.* (1966) again found a large diurnal tidal motion in the wind and a diurnal temperature amplitude in close agreement with the February 1964 results.

2. Instrumentation and data acquisition

The instrumentation consists of a single channel telemetering unit, operating at 1680 mc, with periodic inflight calibration in conjunction with a 0.32-mm bead thermistor as the environmental sensor (Clark and McCoy, 1965). The payload is deployed on a 4.6-m diameter metalized parachute at rocket apogee and tracked with precision instrumentation radars (AN/FPS-16) for accurate position data. The temperature is measured continuously during parachute descent except for 10-sec calibration references at approximately one-minute intervals, and the data are recorded and reduced in much the same manner as balloon-borne radiosonde data.

The instrumentation used for the two series in 1965 had been significantly improved by eliminating heat conduction through the leads to the thermistor, and the heat conduction correction, which is the only important one in the region of interest, was thus obviated. This was accomplished through the use of a thin film mount for the thermistor. Since the thin film mount has a superior surface-area-to-mass ratio relative to the bead and, consequently, a faster response, the temperature gradient between the mount and sensor is reversed.

A recent re-evaluation by Ballard (1966), both

TABLE 1. Meteorological rocket firing times (MST) of the summer and fall series, 1965, at White Sands Missile Range, N. Mex.

1st series Day & month	Hour	2nd series Day & month	Hour
30 June	1430*	9 Oct.	0618
	2000*		1200*
1 July	0200*		1822*
	0800*		2345*
	1112	10 Oct.	0430
	1705*		0600*
	2300*		0900
2 July	1100*		1500*
			2100*
		11 Oct.	0300*
			0920*
			2220

* Soundings used for harmonic analysis.

theoretically and experimentally, confirms Wagner's (1961, 1964) earlier work regarding the effect of solar radiation on the bead thermistor which amounts to approximately 1.5–2C. The geometry of the instrument is such that the bead is out of the sunlight most of the time, but periodically during descent the sun is incident on the bead as the parachute oscillates. The solar radiation effect during these periods, however, is easily discernible on the temperature recording and is eliminated as the data are reduced. Even during the early morning and late afternoon hours, when one would expect the bead to be continuously exposed to the sun, the parachute oscillations periodically remove the bead from the sunlight so that the magnitude of the solar effect can still be detected and subtracted.

For these two series, hypsometer-type radiosonde data were obtained in direct support of the firings to provide maximum reliability of the "tie-on" pressures in the vicinity of 30 km. From these "tie-on" levels, pressure and density were derived for each sounding to the maximum height of the temperature measurement utilizing the hypsometric equation and the equation of state (Thiele, 1961).

3. Discussion of pressure results

Although the description of oscillations in the general vicinity of the stratopause is of primary concern, the pressure distribution over the complete altitude range of the soundings beginning at 30 km is shown in Figs. 1 and 2. It can readily be seen that significant variations do not occur below about 45 km. The maximum and minimum values in this lower region do, however, coincide with day and night respectively as they do at the higher altitudes. Before going further, it should be noted in Fig. 1 that the marked decrease in the range of variability between the maximum and minimum

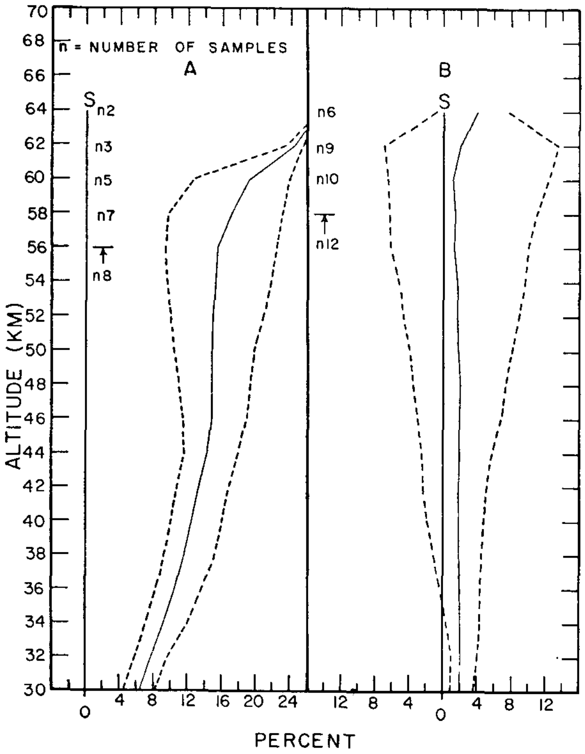

FIG. 1. Per cent variation of the mean pressure of each 48-hr series with respect to the 1962 U. S. Standard Atmosphere (S) and the per cent variation of the extremes about the mean. (A) summer series, (B) fall series.

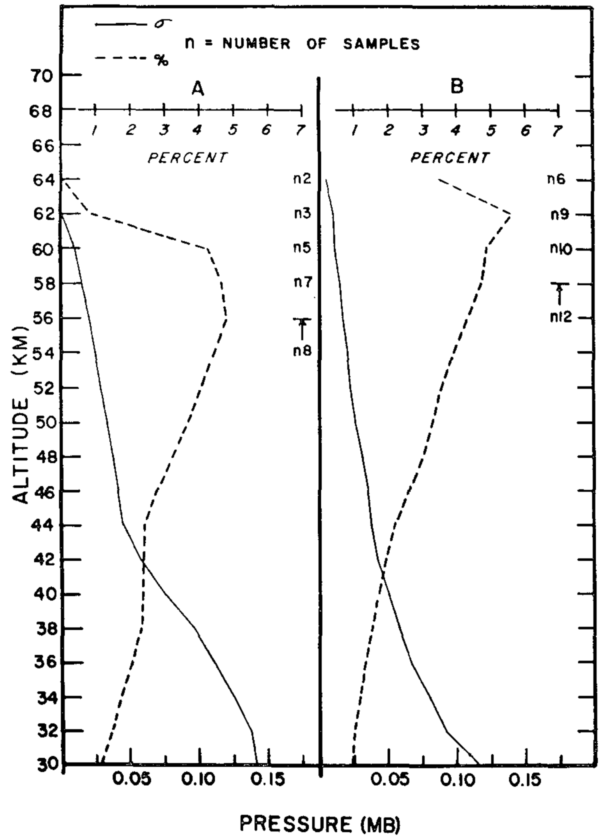

FIG. 2. Standard deviation and per cent of variation of the standard deviation with respect to the mean of pressure. (A) summer series, (B) fall series.

profiles at approximately 60 km is directly attributed to a reduction in data samples. The data are insufficient to infer an upper limit to the region of maximum variability.

The mean pressure profiles, illustrated in A (summer) and B (winter) of Fig. 1, agree with previous seasonal means for this location of approximately 32 degrees latitude (Thiele, 1961, 1963). The 1962 U. S. Standard Atmosphere for pressure (45 degrees latitude) is included in Fig. 1 as a general reference. Since the 1962 standard is an annual mean, it should more closely represent the spring or fall condition, and the good agreement of the October mean with the 1962 standard is therefore consistent. However, the slightly higher value, approximately 2 per cent, of the October mean is at least partially explained by the latitude difference of about 13 deg. Fig. 2 is included to describe the pressure versus altitude in terms of the standard deviation and the per cent of variation of the standard deviation with respect to the mean. This presentation implies the greater variability of the data points at higher altitudes, whereas in Fig. 1 only the variation of the maximum and minimum during each series is represented. Again the sudden decrease in variability at the end, as shown by the percentage curve, is related to a decrease in data samples at the upper altitudes.

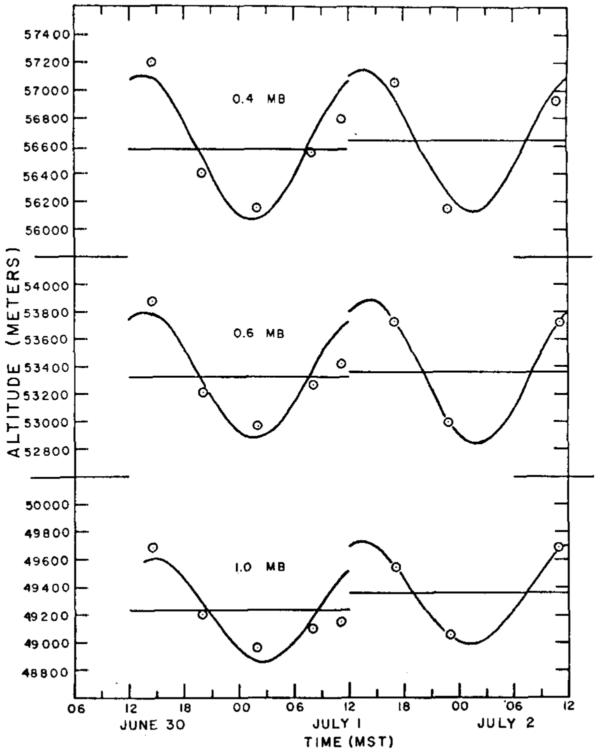

FIG. 3. First harmonic of the heights of the 1.0-, 0.6- and 0.4-mb pressure surfaces for the summer series.

The oscillations of selected pressure surfaces are shown in Figs. 3 and 4 to describe the diurnal variation more clearly. The observations used for the harmonic analyses are noted in Table 1 and the harmonic data in the general format suggested by Haurwitz (1964) are given in Table 2. For the analysis of the second day in the June-July series, an interpolated data point was supplied at 0500 on 2 July to provide the necessary 6-hr spacing. The curves are plotted about the mean height of the data points of each day to minimize any masking by a longer term trend. The slight upward

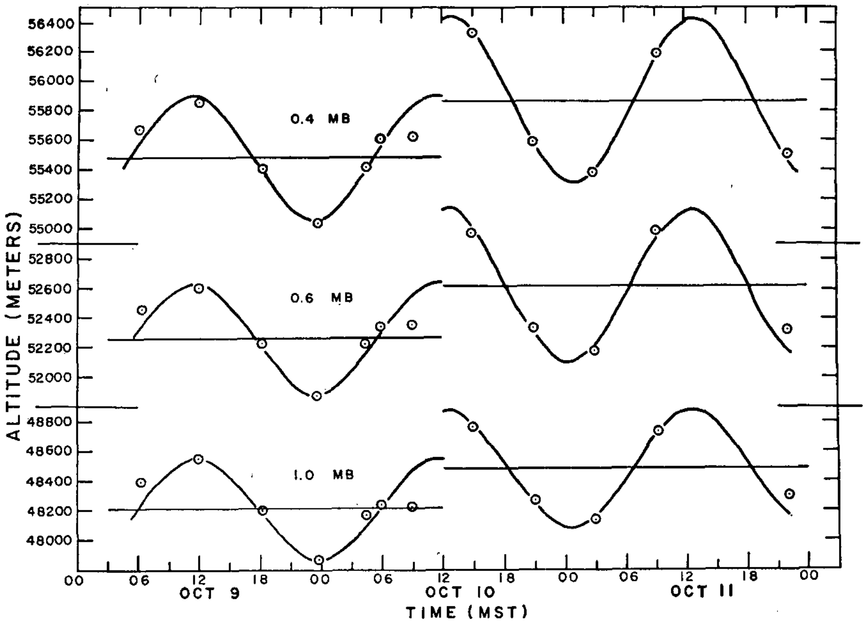

FIG. 4. First harmonic of the heights of the 1.0-, 0.6- and 0.4-mb pressure surfaces for the fall series.

TABLE 2. Harmonic data of the 1.0-, 0.6- and 0.4-mb pressure heights. The amplitudes are in meters and times are MST.

					Summer series					
Pressure surface (mb)	1st day					2nd day				
	a	b	A	α	t_m	a	b	A	α	t_m
1.0	362	59	366	231	1430	198	−312	368	253	1315
0.6	455	−30	455	244	1345	380	−365	526	239	1400
0.4	520	−71	524	248	1330	326	−394	511	245	1330
	1st and 2nd day combined					Semidiurnal from combined data				
0.6	491	−9.7	491	241	1400	92	−7.5	93	035	1400
					Fall series					
Pressure surface (mb)	1st day					2nd day				
	a	b	A	α	t_m	a	b	A	α	t_m
1.0	334	−23	335	274	1145	313	−233	390	262	1230
0.6	370	−50	373	278	1130	395	−325	511	264	1230
0.4	405	−85	414	282	1115	467	−295	551	257	1245
	1st and 2nd day combined					Semidiurnal from combined data				
0.6	440	−0.25	440	270	1200	−25	−40	47	213	2000

trend over the 48 hours during the June-July series (Fig. 3) is not particularly significant; however, a considerable increase from the first to the second day in the mean heights of the pressure surfaces during the October series is apparent (Fig. 4). In both series, exceptionally good agreement of the diurnal pressure wave is obtained between the successive days when comparing the data points in terms of height above or below its mean relative to the mean of the opposite day. This, of course, is a simplified comparison since one would expect the trend to be more linear; however, an analysis of the composite data of the 0.6-mb level for each series with the trend extracted showed no significant difference. Also this same analysis did not show a significant semidiurnal pattern. The semidiurnal amplitudes were one fifth or less of the diurnal amplitudes.

The phase of the diurnal oscillations is also in exceptionally good agreement even though the data are not especially plentiful. The maximum and minimum in these curves (Figs. 3 and 4) are found shortly after noon and midnight, respectively. Webb (1965) has considered the effect of heat losses through thermal radiation, diffusion and eddy mixing from the stratopause region along with the geometric heat input variation and concluded that a sharp crested heated ridge would be formed with a maximum shortly after noon and a minimum near sunrise. Instabilities associated with increased lapse rates above the heating maximum and the velocity of the wave should sharpen the crest of the wave, and the nighttime gradients (controlled by thermal radiation only) should be relatively small. The results obtained through analysis of the data utilized here appear to be in good agreement with theory except that the diurnal minima are too early. Obviously, more data will be required to determine the shape of the diurnal pressure wave.

It is also clear that the data are insufficient in number to infer any phase shift with altitude. Although the times of maximum in Table 2 indicate a shift to earlier occurrence with altitude during the first day of each series, there is no consistent trend apparent during the other two days.

As a possible verification of the observed height changes, a geostrophic flow was assumed in order to make a simple computation of the mean east-west slope based on the average amplitude of the observed diurnal oscillations of the meridional component of the wind. Utilizing the geostrophic expression in the form

$$\partial p/\partial x = \rho f v,$$

and substituting from the hydrostatic equation, the east-west slope of a constant pressure surface can be expressed by

$$dz/dx = fv/g,$$

where x is positive toward the east, f the coriolis parameter, v the north-south wind component, ρ density, p pressure, g gravity and z height. To obtain the total diurnal height change (dz), a value of one half the earth's circumference at 30 degrees latitude was substituted for the distance change (dx) over a 12-hr period.

TABLE 3. Amplitudes of diurnal height changes of constant pressure surfaces in meters.

			30 June–2 July			
	1st day			2nd day		
Pressure (mb)	Observed	Harmonic	Computed	Observed	Harmonic	Computed
1.0	362	366	582	312	368	457
0.6	455	455	499	365	526	400
0.4	520	524	345	455	511	432
			9–11 October			
	1st day			2nd day		
Pressure (mb)	Observed	Harmonic	Computed	Observed	Harmonic	Computed
1.0	335	335	409	313	390	322
0.6	370	373	367	395	511	202
0.4	405	414	100	467	551	520

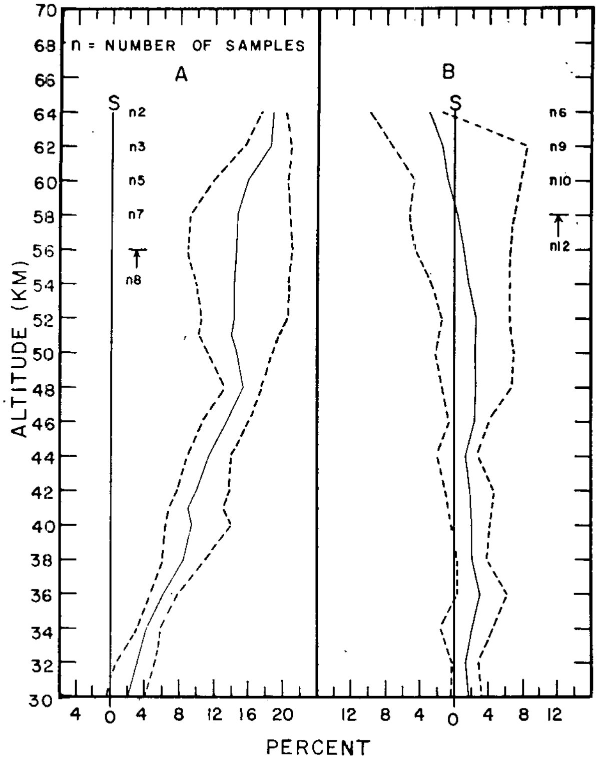

Fig. 5. Per cent variation of the mean density of each 48-hr series with respect to the 1962 U. S. Standard Atmosphere (S) and the per cent variation of the extremes about the mean. (A) summer series, (B) fall series.

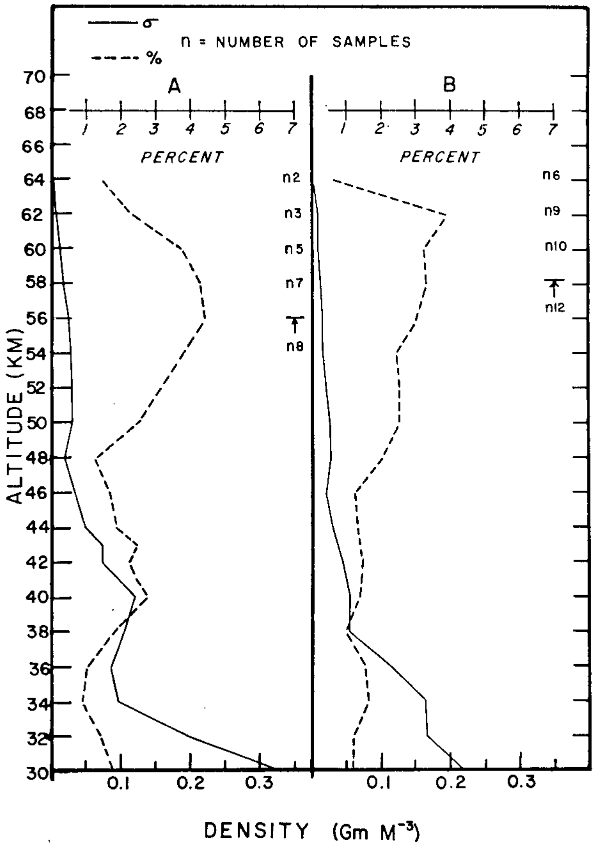

Fig. 6. Standard deviation and per cent of variation of the standard deviation with respect to the mean of density. (A) summer series, (B) fall series.

In addition to the geostrophic assumption, it was assumed that the hydrostatic equation is valid and that the average amplitude of the diurnal meridional wind, taken from an harmonic analysis (Beyers *et al.*, 1966), is valid over the 24-hr period. Also v is taken at the mean altitude of each pressure surface. Table 3 contains the results of this computation in terms of amplitude. The "Observed" height change for each day represents the maximum range measured from approximately noon of one day to the next. These observed maxima and minima do not necessarily represent the extremes since the times are generally not coincident with times of expected maxima and minima. The third column under "Harmonic," however, does represent the extremes as determined by a first harmonic analysis of the observed 1.0-, 0.6- and 0.4-mb pressure surfaces.

The reasonably good agreement of the computed values, with a few exceptions, is rather striking in view of the many assumptions, not the least of which is that of geostrophic flow, and admittedly, such an approach is a vast oversimplification of the problem. Of particular importance is the fact that most of the time, accelerations in the zonal flow were evidenced by the soundings and du/dt, therefore, was seldom zero. But the difficulty in evaluating du/dt was its erratic phase which was essentially impossible to correlate with the phase of the meridional component or with the approximate phase of the pressure oscillations. It is suggested that there may be some cancelling effect in the zonal accelerations which would tend to produce something approaching a geostrophic condition, or more precisely, an *effective* geostrophic condition and therefore account for the relatively good agreement between the observed and computed pressure height amplitudes in most cases.

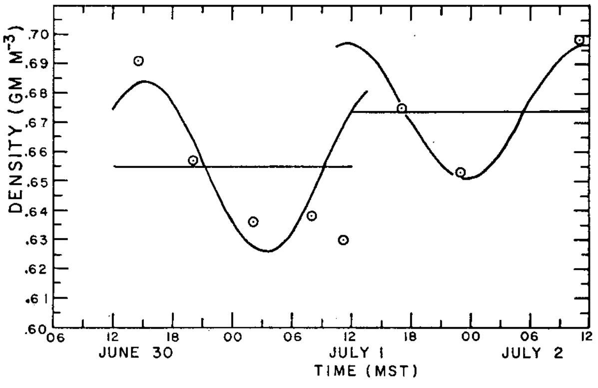

Fig. 7. First harmonic of the density averaged through the 52–58 km layer for the summer series.

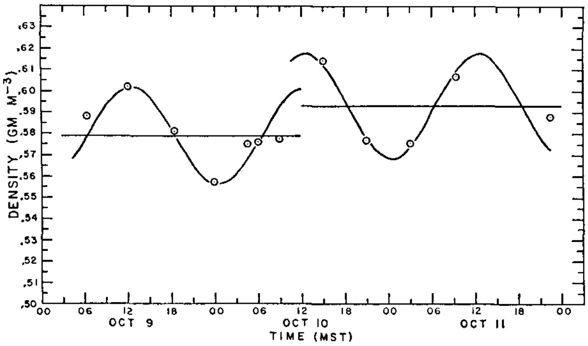

Fig. 8. First harmonic of the density averaged through the 52–58 km layer for the fall series.

4. Discussion of density results

Since the same basic temperature and height data are also used for computing density, the distribution of density with altitude (Figs. 5 and 6) for the two series is, of course, similar to that of the pressure. The relationship with the 1962 U. S. Standard Atmosphere (Fig. 5) is also very similar to the pressure comparison in the foregoing section, and the mean of each series is again in good agreement with local seasonal means of density for summer and fall (Quiroz, 1961; Thiele, 1961, 1963).

Since levels of constant density are not easily obtainable without special computations, the average density for each sounding through the 52–58 km layer was used for an harmonic analysis of the density (Figs. 7 and 8). The mean altitude of these density values is then in the vicinity of 54 km.

An upward trend from the first to the second day is again apparent in both series, but in contrast with the pressure data, there is a more pronounced trend in the June-July series. While this appears to be partially true, the effect is obviously influenced by the 0800 sounding on 1 July, which is one of the end points utilized in the harmonic analysis. This also appears to influence the time of maximum on 30 June. Otherwise the phase of the diurnal density oscillations is in general agreement with that of pressure. The amplitudes also remain consistent (Table 4). With the exception of the somewhat larger amplitude during the first day of the summer series, they are almost identical.

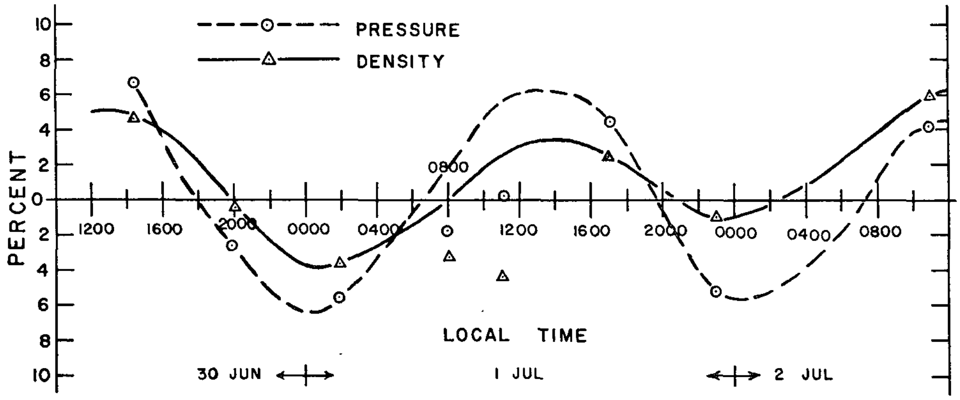

Fig. 9. Per cent variation about the 48-hr mean of pressure and density averaged through the 52–58 km layer, summer series.

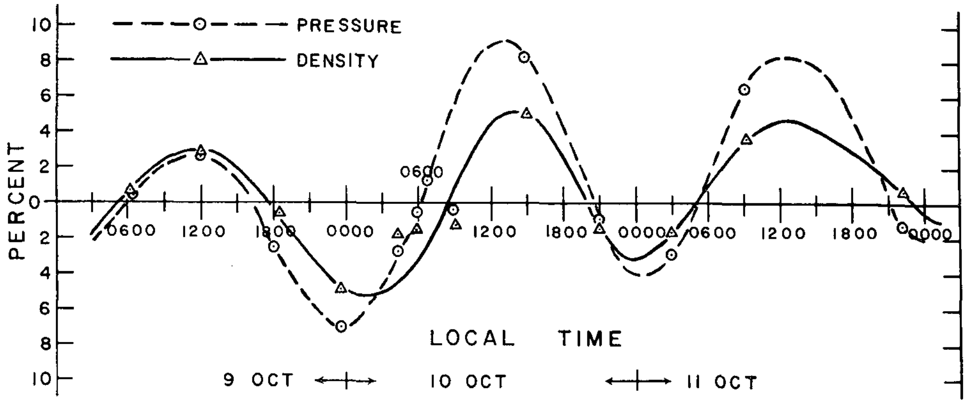

Fig. 10. Per cent variation about the 48-hr mean of pressure and density averaged through the 52–58 km layer, fall series.

TABLE 4. Harmonic data of the density averaged through the 52–58 km layer. Amplitudes are in gm m^{-3} and times are MST.

	1st day					2nd day				
	a	b	A	α	t_m	a	b	A	α	t_m
30 June–1 July	0.027	0.010	0.029	221	1515	0.003	−0.023	0.023	276	1145
9–11 October	0.022	0.003	0.023	264	1230	0.019	−0.015	0.025	263	1230
	1st and 2nd day combined					Semidiurnal from combined data				
30 June–1 July	0.023	−0.002	0.023	245	1345	0.008	−0.002	0.008	042	1345
9–11 October	0.023	0.003	0.024	263	1230	0.000	0.001	0.001	022	1430

5. Summary and conclusions

To summarize the most active region of the atmosphere within the sounding capabilities of meteorological rockets, which is centered near 55 km, pressure and density values were averaged through the 52–58 km layer to provide a general description of diurnal variations in the lower mesosphere. Figs. 7 and 8 show these layer-averaged pressure and density values for each series in terms of percentage of variation with respect to the mean of each series. The curves represent a subjective analysis primarily for the purpose of continuity. Although this subjective analysis, as well as the harmonic analysis, indicates extremes somewhat larger than the observed values, the variability of the actual data is not insignificant. The diurnal range of the observed pressure and density variation is consistently around 10 and 7 per cent, respectively. One can readily see that even this much variation is nearly as great as the seasonal change between the means of the two series. This suggests that monthly and seasonal "standards," at least for approximately 30 degrees latitude between about 40 and 60 km, should include a departure value for the nighttime minimum, particularly since the majority of all data used for standards is biased toward daytime values. As pointed out in the introduction, nearly all meteorological rocket measurements have been made during daylight hours.

The remarkable consistency of the diurnal oscillations of pressure and density throughout two 48-hr series leaves little doubt regarding the strong solar influence on the upper stratosphere and lower mesosphere. However, as pointed out earlier, more concentrated data will be required, and probably during all seasons, to define the times and magnitudes of pressure, density and temperature extremes adequately, and for determining the existence of a significant semidiurnal pattern.

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