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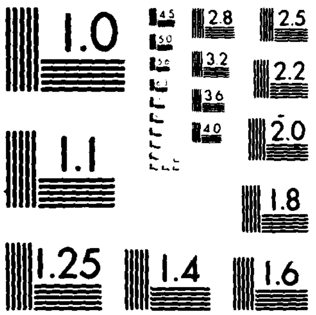

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Variations of Density and Wind With Time at Altitudes 30 to 60 km

ARTHUR J. KANTOR
ALLEN E. COLE

22 September 1981

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METEOROLOGY DIVISION PROJECT 6670
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HANSCOM AFB, MASSACHUSETTS 01731

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Information on the horizontal and vertical distributions of density and wind and their variation with time is important in the design and operation of aerospace vehicles as well as to atmospheric scientists seeking a more precise description of atmospheric structure. Consequently, we have estimated the variations of density and wind at seven locations for periods of from 1 to 72 h between altitudes 30 and 60 km.

In the tropics density variations with time are dominated by a diurnal cycle. At other latitudes the diurnal cycle is too small to detect in a lag

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20. Abstract (Continued)

variability study based on Meteorological Rocket Network observations because the diurnal components are obscured by random observational errors as well as day-to-day changes in synoptic conditions. In summer there is only a small increase in rms variability of density with time at middle and high latitudes; rms values range from 2 to 4 percent for periods up to 72 h. In winter there is a marked change in the rms variability with time at midlatitudes where rms values increase with time, approaching the climatic variability of 5 or 6 percent in 72 h. At high latitudes rms variations increase more rapidly with time and reach 8 or 9 percent within 72 h.

Analyses of midlatitude wind data between 30 and 60 km confirm the presence of a well-defined diurnal wind oscillation. It reaches a maximum amplitude of 10 or 11 m/sec between 50 and 55 km; amplitudes tend to be slightly smaller in tropical and polar regions.

Preface

The authors wish to thank Mr. Eugene A. Bertoni who supervised the data collection and computations involved in preparing the data for analysis. We commend the efforts of Ms. Nancy Cobb who did much of the statistical analysis and completed most of the figures in this report. Finally, we also extend our thanks to Mrs. Helen Connell who typed several drafts of the text and tables.

Contents

Illustrations

Illustrations

Tables

Variations of Density and Wind With Time at Altitudes 30 to 60 km

1. INTRODUCTION

Knowledge of horizontal and vertical distributions of atmospheric density and wind is important in the design and operation of aerospace vehicles, as well as to atmospheric scientists seeking a more precise description of atmospheric structure. Information on time variations of these elements is required by the U.S. Air Force in designing and testing such vehicles. For example, during reentry tests of ballistic missile nose cones, the Air Force needs to know how well observations taken at the reentry point within several hours or days of actual reentry, represent conditions encountered by the reentry vehicles.

In order to provide answers to these questions, we have estimated the variations of density and wind with time at seven locations for periods ranging from 10 min to 72 h between 30 and 60 km. This investigation is part of a continuing Air Force Geophysics Laboratory (AFGL) effort to compile and analyze information on the distribution of wind and the thermodynamic properties of the atmosphere, and to provide mathematical models or summaries of such data that are suitable for use in design and operation of guidance systems of aerospace vehicles.

(Received for publication 18 September 1981)

2. DATA SOURCES AND ACCURACY

Density and wind data used in this report consist of Meteorological Rocket Network (MRN) observations taken at the seven locations in Table 1. Observations of the thermodynamic properties consist primarily of temperatures as recorded by thermistors attached to parachutes that are usually released at 65 to 70 km. Pressures and densities are then computed from the hydrostatic equation and perfect gas law.

Table 1. Observational Sites

Station	Location		Period of Record
Ascension Island	$8^{o}S$,	$14^{o}W$	1969-1976
Kwajalein	$9^{o}N$,	$168^{o}E$	1969-1978
Fort Sherman	$9^{o}N$,	$80^{o}W$	1969-June 1977
White Sands	$32^{o}N$,	$106^{o}W$	1969-1976
Wallops Island	$38^{o}N$,	$75^{o}W$	1969-1978
Churchill	$59^{o}N$,	$94^{o}W$	1969-June 1977
Poker Flats	$64^{o}N$,	$146^{o}W$	1969-1976

Density at a given level is dependent upon the integrated temperature profile through a substantial layer of the atmosphere rather than from an observed temperature at a specific altitude. Consequently, random observational errors in temperature tend to average out in the integration over the entire layer, minimizing the random errors in computed densities. The root-mean-square (rms) errors in densities derived from rocketsonde temperature measurements have been estimated to vary linearly from 1 percent at 30 km to 4 or 5 percent at 60 km.[1]

North-south and east-west wind components were obtained for 2-km height increments directly from the MRN observations that have been determined by tracking the path of rocket-launched parachutes with radar. The rms observational errors in these rocketsonde wind measurements between 30 and 60 km have been estimated to be 2 m/sec plus 3 percent of the vector wind.[1]

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[1] Meteorological Group, Range Commanders Council (1977) Meteorological Data Error Estimates, Document 110-77, White Sands Missile Range, New Mexico.

3. TECHNIQUE

Analyses of the diurnal variations of density at altitudes above 30 km have been severely hampered by a general lack of observations "around the clock." However, on a few occasions and at one or two locations, a special series of observations has been completed. At Ascension Island, for example, 24 ARCAS rockets carrying Arcasonde 1A instrumentation were launched in a 48-h period during 11 to 13 April 1968. This was one of the early efforts to obtain information on diurnal variations in atmospheric structure at altitudes between 30 and 60 km.

Data derived from these soundings were analyzed to obtain estimates of the amplitude and phase of the diurnal oscillations in density. The 50-km densities, plotted vs local time, are shown in Figure 1. Densities are given as percent departures from the 1976 U.S. Standard Atmosphere. The dots are observed values and the x's represent averages of observations taken within 3 h of each other. The eight average values were subjected to harmonic analysis, and the solid curve represents the sum of the first and second harmonics for the 48-h period. An F test indicates that the second harmonic, which represents a diurnal (24-h) oscillation in density with an amplitude of roughly 4 percent (a range of 8 percent), is significant at the 1 percent level; it reduces the observed variance of the data by 91 percent.

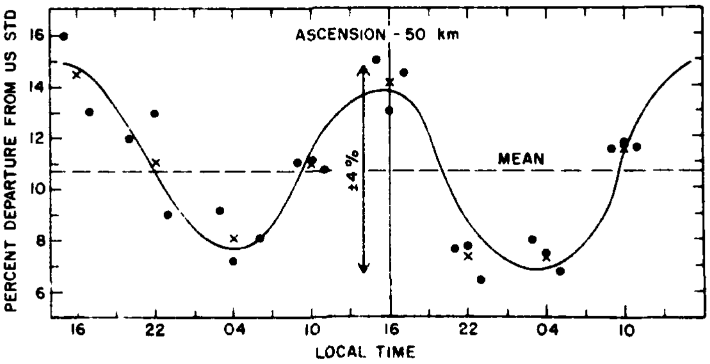

Figure 1. Diurnal Density Variation at Ascension Island. Dots are observed values, x's represent 3-h averages, and the solid line is the computed diurnal cycle

The rms differences between density observations for various time intervals also can be used as a measure of the change in density with time at a given altitude. For the same set of soundings at Ascension, the computed rms differences between observations 1 to 36 h apart are shown in Figure 2 as a function of time for altitudes from 35 to 60 km. Also shown is the number of pairs of observation available for each time interval. Since at time T = 0 the rms change in time and space is zero, an estimate of the random observational error can be obtained from the observations themselves by extrapolating the plotted curves in Figure 2 back to zero hours. This procedure indicates that the random rms observation errors are approximately 1 percent at 35 and 40 km, and 1.5 to 2.0 percent at altitudes between 45 and 60 km. These values are in rough agreement with the estimated 1.3 percent rms observational errors found by Nee[2] for radiosonde density measurements at 25 km. They are, however, slightly smaller than the estimates given in Section 2 of this report.

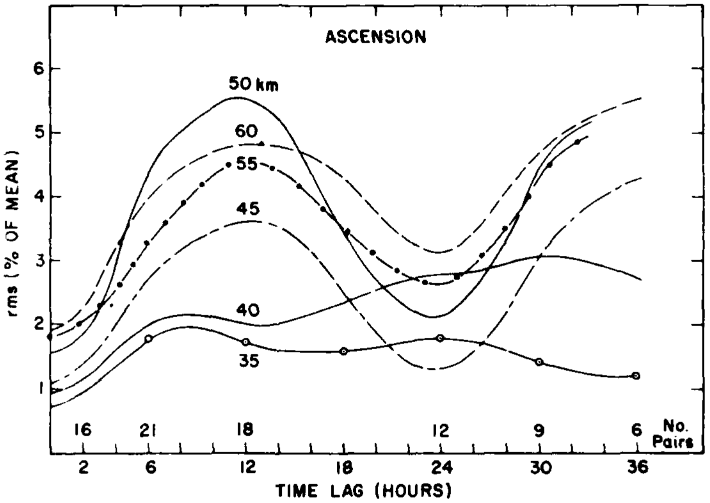

Figure 2. Rms Lag Variability of Density With Time at Ascension Island

If there were no well-defined periodic oscillations within a 24-h period, the rms variability of density would be expected to increase smoothly with time until it reached a value representing the climatic value (the day-to-day variability around the monthly mean). The data presented in Figure 2 show that the change

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[2] Nee, P.F. (1964) Hourly variability of density at radiosonde heights, *J. Applied Meteor.* 3:175-178.

in the rms variability of density with time at 35 km is relatively small, remaining between 1 and 2 percent of the daily mean for the 36-h period. The variability at 40 km is similar to that at 35 km for the first 12 h, after which the rms values increase almost linearly with time, reaching a maximum of nearly 3 percent at 32 h. A well-defined 24-h oscillation appears in the rms density variations at all altitudes above 40 km, with maximum variations at 12 and 36 h and a minimum at 24 h. The 12-h amplitudes of the 24-h cycle increase with altitude; they approach ±4 percent at 50 km, and then decrease to about ±3 percent at 55 and 60 km.

The magnitude of the 50-km variations at time lags of 12 and 36 h (Figure 2) are almost as large as those shown by the harmonic analysis in Figure 1. This indicates that this type of lag-variability analysis can provide reasonable estimates of the magnitude of the diurnal cycle as well as estimates of the variability of density with time. In this particular example, the size of the diurnal cycle increases with altitude, reaching a maximum at 50 km and decreasing slightly at 55 and 60 km. The rapid increase in density variability above 40 km is probably a result of the diurnal temperature oscillation between 35 and 45 km that is caused by heating and cooling of the ozone layer. The decrease in variability above the stratopause (55 and 60 km) could be a reflection of a slight decrease in amplitude of the diurnal temperature oscillation above 45 km.

For this report we have analyzed the rms differences between density observations taken from 10 min to 72 h apart. Our objective was to obtain estimates of the temporal variations of density during various seasons and over various geographic regions for periods of 1 to 72 h. This should also provide us with an indication of the magnitudes of the diurnal density cycles for the locations shown in Table 1. All of the observations that were separated by less than 72 h were used in this analysis. MRN observations are usually taken at or near midday; consequently, there is a preponderance of values for time lags of 24, 48, and 72 h. There are, however, sufficient observations over the 8- or 9-year period to afford useable data for many of the other time lags between 1 and 72 h.

4. DENSITY

The computed rms differences between densities observed 1 to 72 h apart are shown in Figure 3 as a function of time for three tropical stations; Ascension Island (8°S), Kwajalein (9°N), and Fort Sherman (9°N). All months are combined in Figure 3 since periodic oscillations have been determined to be nearly the same during all seasons over tropical regions.[3] The x's are rms values based on

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[3] Cole, A.E. (1981) Time and Space Variations of Density and Temperature between Altitudes of 25 km and 80 km, Third Conference on the Meteorology of the Upper Atmosphere, 20-22 January, San Diego, California.

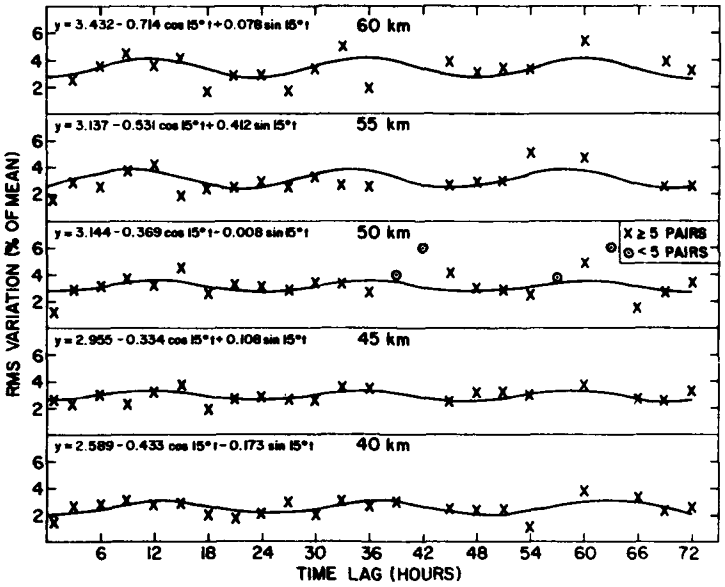

Figure 3. Rms Differences Between Densities Observed 1 to 72 h Apart in the Tropics

differences from at least five pairs of observations; the dots, shown only at 50 km, are rms values based on fewer than five pairs. The curves, as described by the given equations, represent 24-h harmonic fits to the x-values at altitudes 40 through 60 km. Linear least-square regression lines (not shown) also were applied to these observations, but at each level the 24-h harmonic curves accounted for a larger percentage of the total variance of the data than the regression lines. The magnitudes of the 24-h harmonic (excluding the observational error) generally increase with altitude, doubling in size from < 1 percent of the annual mean at 45 km to 1 1/2 or 2 percent at 60 km. Since diurnal density variations are as large or larger than the day-to-day variations in tropical regions,[4] these data indicate that an observed density profile between 30 and 60 km in the tropics is more representative of conditions 24 h later than it is of conditions 6 to 12 h later.

Computed rms differences between densities observed 1 to 72 h apart are shown in Figures 4 and 5 for White Sands Missile Range (32°N). As in Figure 3, the x's are rms values based on differences from at least five data pairs, and the dots at 50 km represent rms values based on fewer than five pairs. Least-square

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[4] Kantor, A.J., and Cole, A.E. (1979) Time and Space Variation of Density in the Tropics, AFGL-TR-79-0109, AD A074 472.

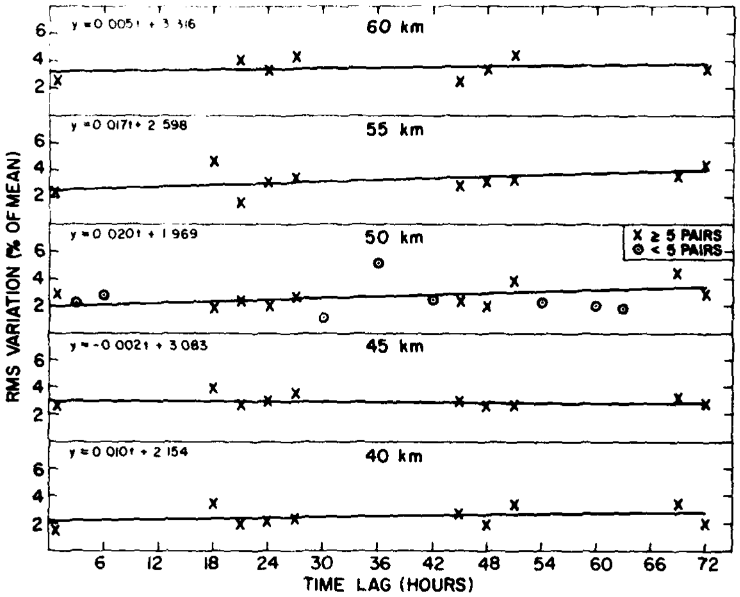

Figure 4. Rms Differences Between Densities Observed 1 to 72 h Apart at White Sands Missile Range in Summer

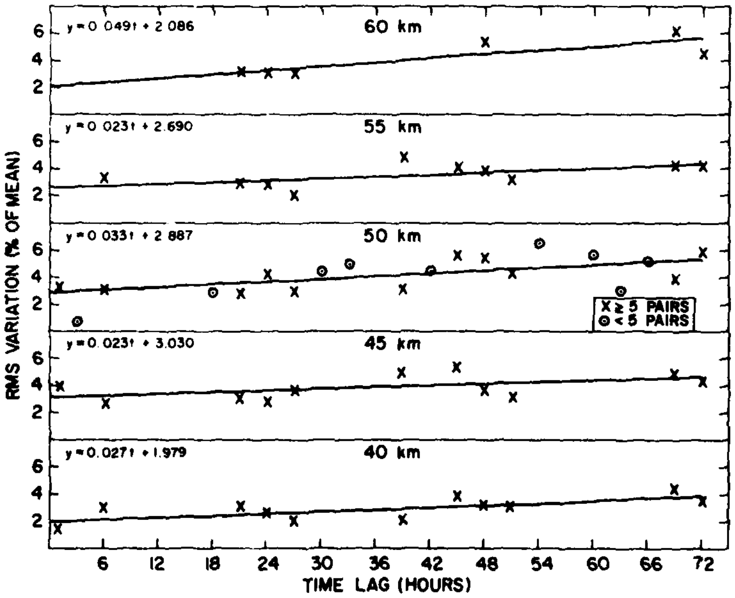

Figure 5. Rms Differences Between Densities Observed 1 to 72 h Apart at White Sands Missile Range in Winter

regression lines have been fitted to the x-values, and their equations are given for altitudes 40 through 60 km. There appear to be no significant diurnal oscillations at these altitudes in either summer (Figure 4) or winter (Figure 5). Any diurnal component is undoubtedly obscured by the random instrument errors and the larger day-to-day variability that occur at these latitudes and altitudes. In summer the rms variability does not change much with time, remaining generally between 2 and 3 percent for the entire period. In winter the rms variations gradually increase with time from 2 or 3 percent until they approach the climatic variability of 5 or 6 percent at 72 h. The regression lines explain from 51 to 81 percent of the total variance of the data at all five levels. Similar conditions were found for summer (Figure 6) and winter (Figure 7) at Wallops Island (38°N), a typical mid-latitude location.

The lag variability of density for time periods up to 72 h is shown in Figures 8 and 9 for Churchill (59°N) and Poker Flats (64°N) together. Observations for the two stations have been combined to increase the sample size, which contains only a few data points clustered around 24, 48, and 72 h. Presentation, including least-square regression lines, is the same as that shown for White Sands Missile Range and Wallops Island. Here too, there is no noticeable diurnal cycle, and in summer (Figure 8), rms variations increase slightly from an estimated 1 1/2 or 2 percent to only 3 or 4 percent at 72 h. Thus, if we assume an rms observation error of 1 1/2 to 2 percent (see Section 2), there is little variation in density at these altitudes during subarctic summer. During winter (Figure 9), however, the rms variability tends to increase more rapidly with time, especially at 45 and 50 km, where it reaches roughly 8 percent in 72 h. This is about 55 percent of the climatic variability of 14 percent that is experienced in winter months at these latitudes and altitudes.[3]

5. WINDS

A series of wind observations on 27 to 28 May 1977 and a second set for August 1977, both at Wallops Island, were analyzed in order to examine the characteristics of the diurnal wind oscillations between 30 and 60 km. Results for the north-south winds in May and August are shown in Figures 10 and 11, respectively, at altitudes 40 through 60 km. The x's are average values at the indicated local times, and the curves, as described by the appropriate equations on Figures 10 and 11, are the diurnal fits to the data. The diurnal amplitudes for both months appear to reach a maximum of 10 or 11 m/sec between 50 and 55 km, and the phases (times of maximum) generally occur between 1200 and 1400 h local time.

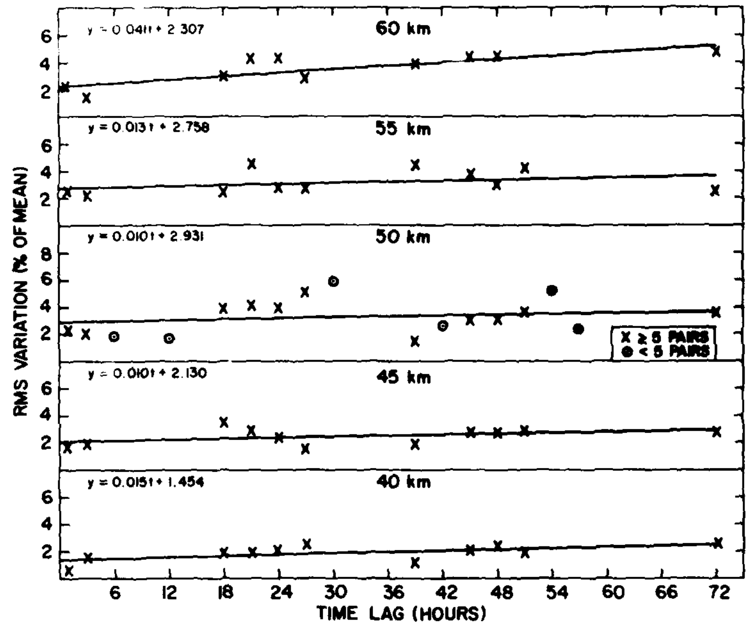

Figure 6. Rms Differences Between Densities Observed 1 to 72 h Apart at Wallops Island in Summer

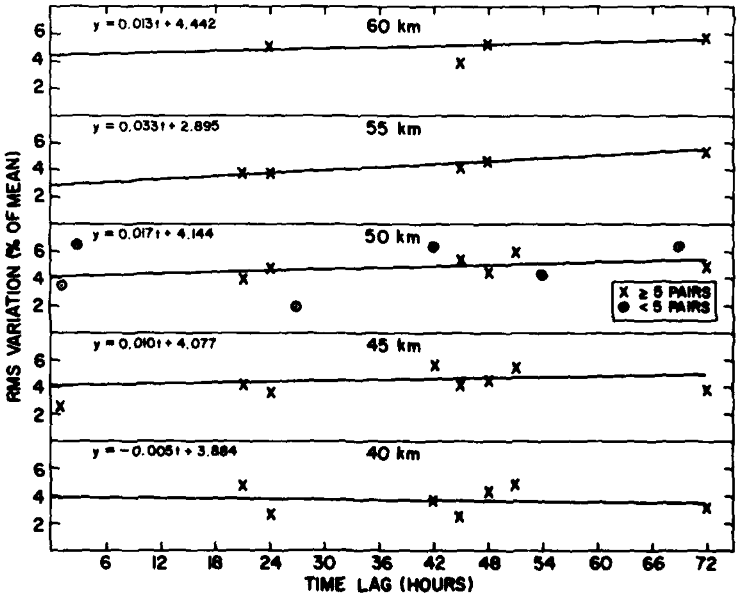

Figure 7. Rms Differences Between Densities Observed 1 to 72 h Apart at Wallops Island in Winter

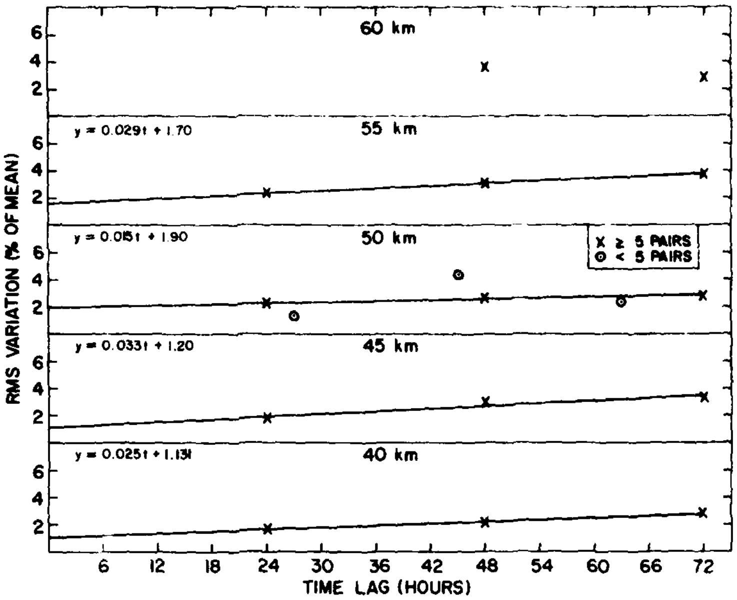

Figure 8. Rms Differences Between Densities Observed 1 to 72 h Apart at Poker Flats/Churchill in Summer

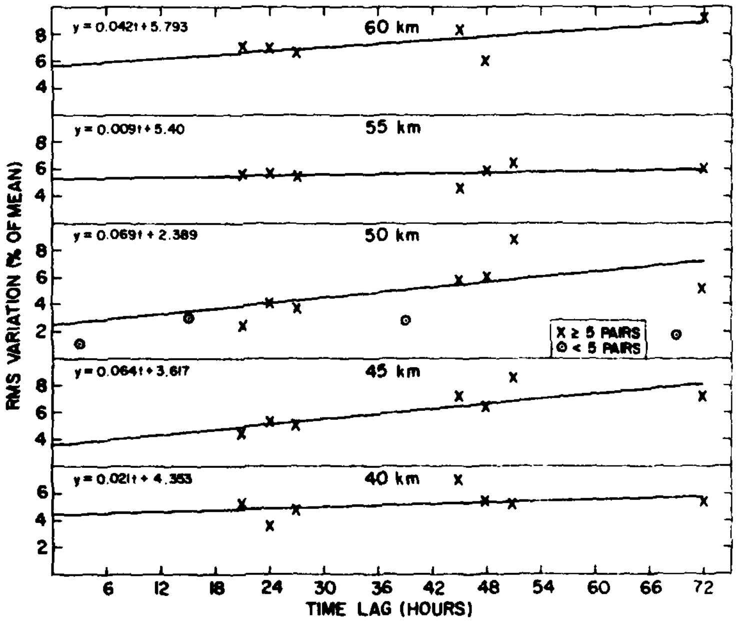

Figure 9. Rms Differences Between Densities Observed 1 to 72 h Apart at Poker Flats/Churchill in Winter

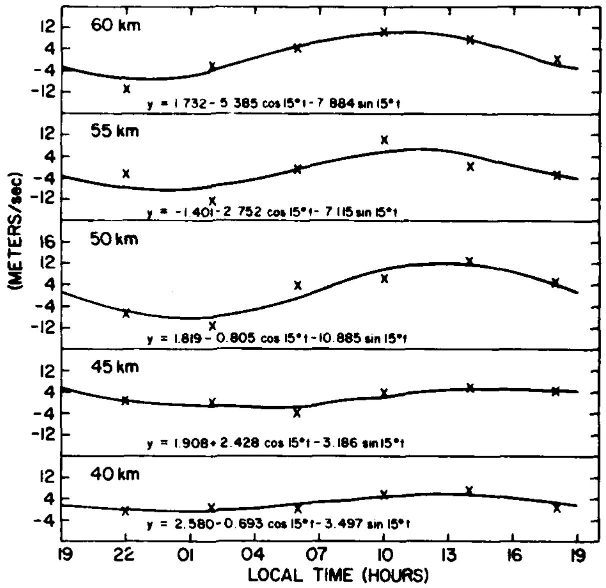

Figure 10. Diurnal North-south Wind Variation at Wallops Island in May

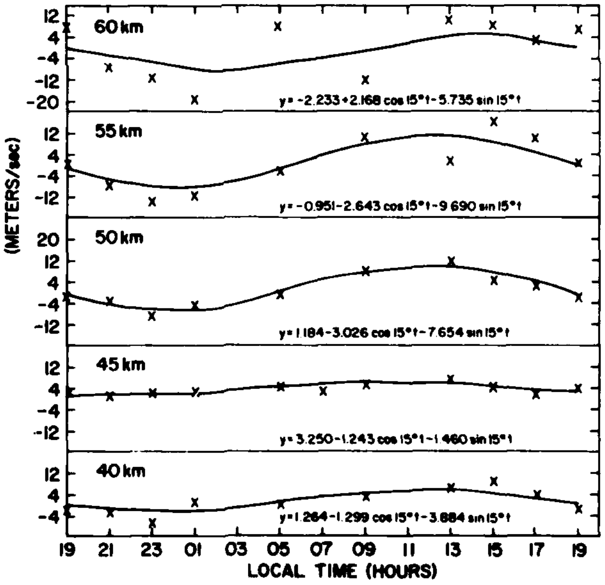

Figure 11. Diurnal North-south Wind Variation at Wallops Island in August

This is in close agreement with the diurnal wind oscillations found by Reed, et al,[5] which, in addition, show that diurnal amplitudes are somewhat smaller in tropical and polar regions. These results indicate that a wind observation in the tropics may be more representative of conditions in 24 h rather than in 6 or 12 h since the diurnal oscillation in tropical regions is as large or larger than the day-to-day variations at these altitudes. In a related study on diurnal wind variations, Groves[6] recently showed that, at latitudes beyond the tropics, diurnal amplitudes in winter may be reduced from those in summer.

Rms differences between values of the north-south wind components observed from 1 to 72 h apart also were analyzed for the seven locations listed in Table 1. Data based on all months combined at the three tropical stations, Ascension Island, Kwajalein, and Fort Sherman, are shown in Figure 12. The x's are rms values based on the differences from at least five pairs of wind observations; the dots, shown at 50 km, are rms values based on fewer than five pairs. Except for the first few hours, values display a relatively stable rms variation of roughly 10 or 12 m/sec for periods up to 72 h at 55 and 60 km, and about 6 or 7 m/sec at 40 and 45 km. There is an indication of a diurnal cycle at these altitudes, as shown by the 24-h harmonic fits to the x-values. The curves, however, account for just a small portion of the total variance of the observations (< 13 percent), and amplitudes are less than 1.5 m/sec. These amplitudes are no larger than the estimated observational errors, which, as a result, tend to obscure the diurnal oscillation. Similar conditions for the north-south components were found in both summer and winter at White Sands Missile Range (Figures 13 and 14), Wallops Island (Figures 15 and 16), and Poker Flats/Churchill (Figures 17 and 18). Rms variations at these locations generally are larger than in the tropics, particularly in winter when the winds are stronger and transient synoptic features are more intense. These features of the circulation pattern in winter tend to obscure the diurnal oscillations at these latitudes and altitudes. The variations with time are approximately the same at all latitudes in summer, with little change in 72 h. In winter the rate of increase in the magnitude of the variations with time varies with latitude. At 50 km, for example, rms values at White Sands Missile Range increase with time from 6 or 8 m/sec to 16 or 18 m/sec in 72 h, and at Poker Flats/Churchill the increase is from 6 or 8 m/sec to 25 m/sec.

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5. Reed, R.J., Oard, M.J., and Sieminski, M. (1969) A comparison of observed and theoretical diurnal tidal motions between 30 and 60 kilometers, Monthly Weather Review 97(No. 6).

6. Groves, G.V. (1980) Seasonal and diurnal variations of middle atmosphere winds, Phil. Trans. R. Soc., Series A 296(No. 1418).

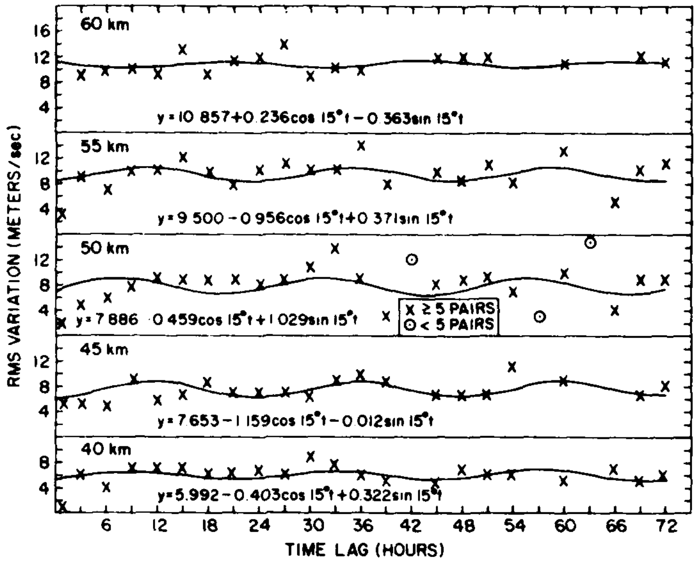

Figure 12. Rms Differences Between North-south Winds Observed 1 to 72 h Apart in the Tropics

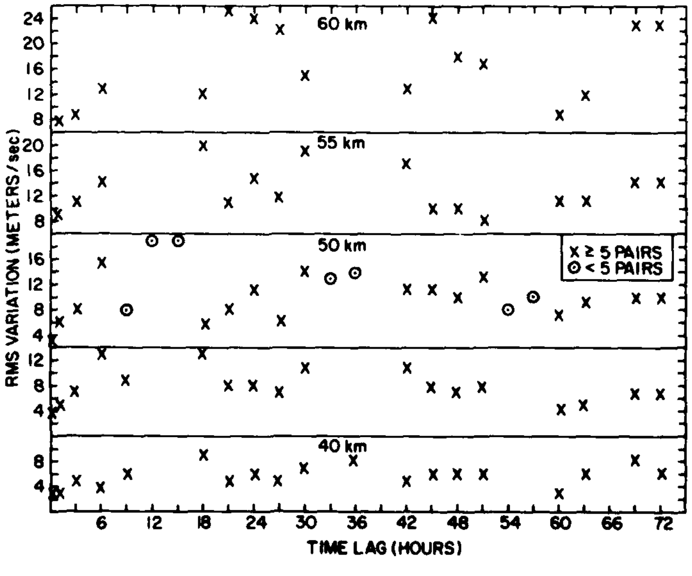

Figure 13. Rms Differences Between North-south Winds Observed 1 to 72 h Apart at White Sands Missile Range in Summer

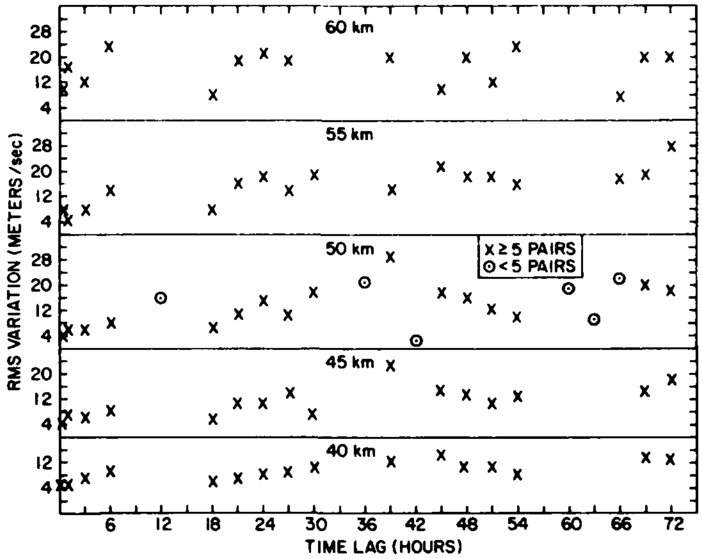

Figure 14. Rms Differences Between North-south Winds Observed 1 to 72 h Apart at White Sands Missile Range in Winter

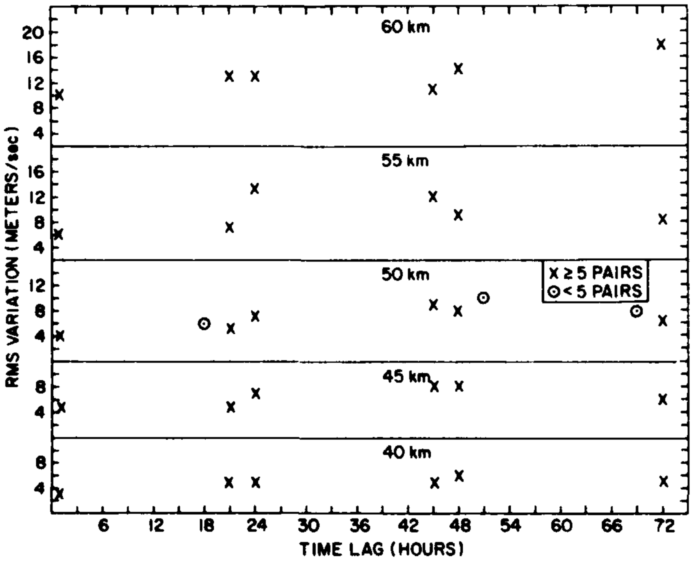

Figure 15. Rms Differences Between North-south Winds Observed 1 to 72 h Apart at Wallops Island in Summer

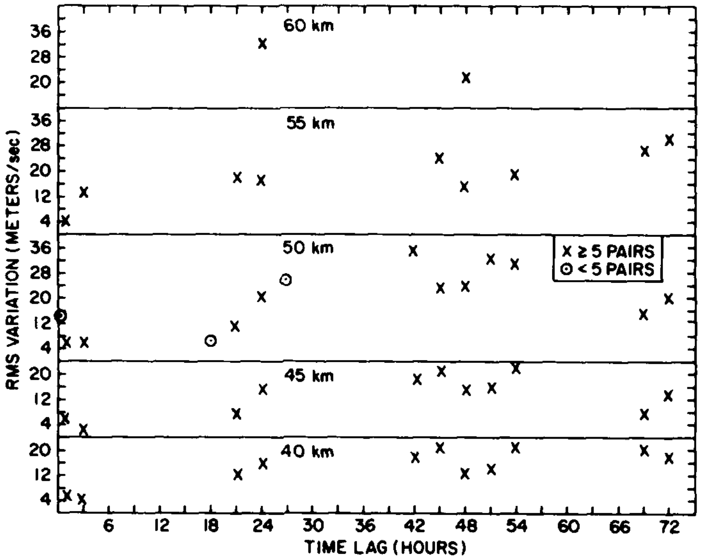

Figure 16. Rms Differences Between North-south Winds Observed 1 to 72 h Apart at Wallops Island in Winter

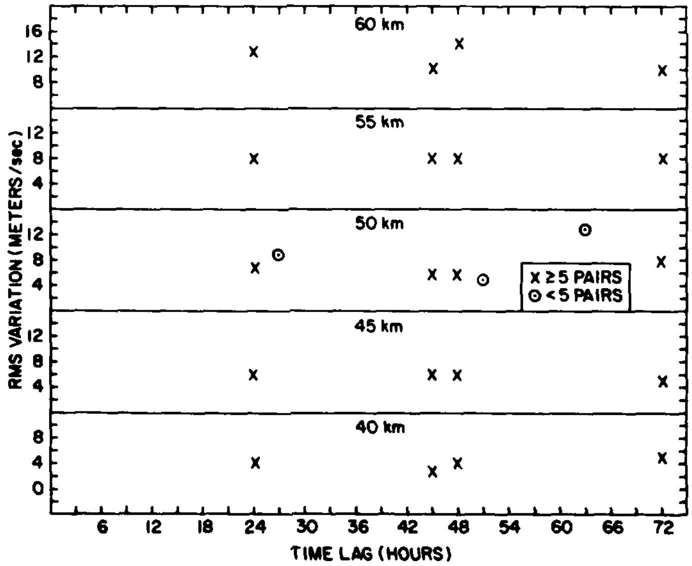

Figure 17. Rms Differences Between North-south Winds Observed 1 to 72 h Apart at Poker Flats/Churchill in Summer

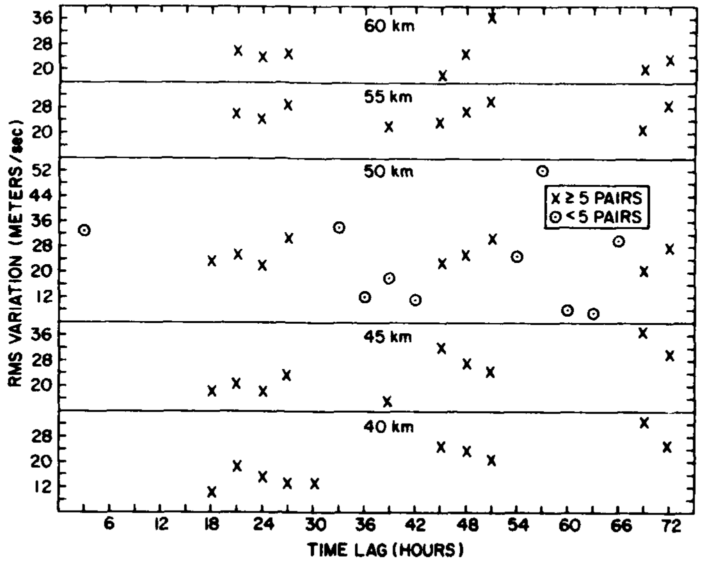

Figure 18. Rms Differences Between North-south Winds Observed 1 to 72 h Apart at Poker Flats/Churchill in Winter

6. FINDINGS

Analyses of available density observations for altitudes between 30 and 60 km provide reasonable estimates of the magnitude (and changes with season and latitude) of the variability of density with time for periods up to 72 h.

In tropical areas the variations of density with time at altitudes between 35 and 60 km are dominated by a diurnal cycle. Amplitudes vary from 1 or 2 percent to 4 percent, depending on altitude and time of year. There is very little day-to-day variability because there are only small changes in synoptic conditions in the tropics. At other latitudes the diurnal cycle is too small to detect in a lag variability study based on MRN observations. The diurnal components are undoubtedly obscured by random observational errors and the larger day-to-day changes in synoptic conditions.

Variations of density with time in middle and high latitudes are relatively small during summer and do not increase significantly with time. Rms variations remain between 1 1/2 and 4 percent for all periods up to 72 h. Consequently, frequent observations are not needed in summer because observed variations are roughly equal to the random observational errors. In winter, the larger day-to-day changes in the synoptic patterns at middle and high latitudes are reflected in the well-defined increase in the rms variations with time. At midlatitude locations the rms variations in density increase with time from 2 or 3 percent until they approach the climatic variability of 5 or 6 percent at 72 h. At high latitudes, where the day-to-day synoptic changes are even larger, rms variations increase more rapidly with time, approaching 8 or 9 percent in 72 h, or almost 60 percent of the observed climatic variability at locations between 55° and 70°N.

Analyses of midlatitude wind observations in May and August for altitudes between 30 and 60 km confirm the presence of a well-defined diurnal north-south wind oscillation. It reaches a maximum amplitude of 10 or 11 m/sec between 50 and 55 km in middle latitudes, but is slightly smaller in tropical and polar regions. An analysis of rms differences between values of the north-south wind components observed from 1 to 72 h apart also indicates that there is a diurnal cycle at these altitudes. However, observational errors and changing synoptic conditions within a 24-h period tend to obscure the diurnal cycle in these analyses. The rms variations of the north-south wind with time approach the climatic values of the day-to-day variability around the monthly mean within 72 h in the tropics, 6 or 7 m/sec near 40 km, and 10 or 12 m/sec at 60 km. Similar conditions exist in both summer and winter at middle and high latitudes. Variability with time, however, is generally larger outside the tropics, particularly in winter.

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2-8