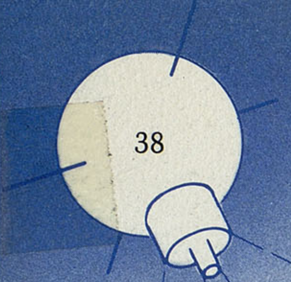

SATELLITE & MESOMETEOROLOGY RESEARCH PROJECT

Department of the Geophysical Sciences
The University of Chicago

STATISTICAL AND KINEMATICAL PROPERTIES OF THE LOW-LEVEL JET STREAM

by

William D. Bonner

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ABSTRACT

Geographical, diurnal and seasonal variations in the frequency of occurrence of strong low-level wind maxima are examined through machine analysis of two years of twice-daily wind observations from 47 rawinsonde stations in the United States. Maximum frequencies of occurrence are found in the Great Plains, centered at approximately 37 deg N and 98 deg W. The vast majority of the jets in this area occur with southerly flow. The Great Plains southerly jet is apparent on late afternoon wind soundings but occurs with much greater frequency, over a larger area, on the morning observations.

A computer printout of "low-level jet days" at various stations is used to select a number of cases for synoptic description of the early-morning southerly jet. Temperature, moisture and wind fields are examined by plotting individual observations in a jet coordinate system. Mean cross sections through the southerly jet are shown and a comparison is made between geostrophic and actual winds near the level of maximum wind. Observed winds are found to be supergeostrophic as expected, however, the low-level jet appears to be a reflection of both geostrophic and ageostrophic wind fields.

1. Introduction

During recent years, a considerable amount of interest has developed in the phenomenon of the low-level wind maximum and, in particular, in the low-level jet stream.

Means (1952, 1954) introduced the term low-level jet to describe a band of strong southerly winds at 2000 to 3000 ft above the ground in the south-central United States which he considered to be important in the formation of midwestern thunderstorms. According to Means, this jet was primarily the reflection of strong, southerly geostrophic winds near the ground which decreased sharply with height under the influence of a warm tongue to the west. While such wind patterns could be expected to be found ahead of an advancing trough, the eastern slopes of the Rockies were, he felt, a preferred region for their formation because of the common occurrence of warm pockets along the eastern slopes of the mountains during the summer months of the year.

Means published a cross section through the jet, showing the geostrophic southerly winds averaged over a one-week period along a line between Little Rock, Arkansas and Albuquerque, New Mexico. A core of strong winds was located at the surface between Amarillo, Texas and Oklahoma City, Oklahoma. While the average geostrophic wind speeds in the jet as described by Means were only approximately 30 knots, in individual cases, the actual winds near the ground during periods of southerly flow in this area can be much stronger. Newton (1956) describes a case in which the wind speeds at 850 mb exceed 50 knots over a several-state area in the Great Plains, reaching a peak speed of over 70 knots in southern Kansas.

A closely-related phenomenon, also called the low-level jet stream, has been described by Blackadar (1957). Wagner (1939), Goualt (1938), Farquharson (1939) and others, working with data from various parts of the world, had shown that winds above the first few tens of meters and below about 2 km show a diurnal oscillation exactly opposite to that of the surface winds. Within this layer, wind speeds typically are strongest at night or early in the morning. In the United States, Wagner found that this oscillation was most pronounced at stations in the Great Plains. Lettau (1954) and Blackadar (1955) pointed out the high frequency with which nighttime low-level wind maxima were observed during the Great Plains Turbulence Field Program at O'Neill, Nebraska, and Blackadar (1957) related these wind maxima or "low-level jet observations" to the diurnal oscillation of the wind near the top of the friction layer. According to Blackadar, such low-level wind maxima are likely to be found anywhere over land during the night but are most likely to occur under clear skies, at localities far from the ocean, where the underlying surface is dry and smooth, and where the geostrophic wind is strong. These conditions are often met during periods of southerly flow over the Great Plains and diurnal oscillation of the wind has been offered as an explanation for the southerly low-level jet in this area.

Strong low-level jet observations are certainly not peculiar to the Great Plains, however. For example, Gifford (1952) traced the evolution of a nighttime wind maximum at Silver Springs, Maryland, where, at maximum intensity, the wind speed at 2000 ft exceeded 40 knots, an excess of 20 knots over the speed at 4000 ft. Nor are these wind maxima restricted to the nighttime hours. Kuettner (1959) has described some daytime wind maxima in the northeastern United States. Hoecker (1963) has shown that the southerly jet in the Great Plains can, on occasion at least, be found during the day as well as at night. Novozhilov (1961) has stated that low-level wind maxima are frequently found during the daytime hours in eastern Europe.

Thus, although theories have been developed to explain nocturnal wind maxima in general and the Great Plains southerly jet in particular, little evidence has been presented to describe the relative frequencies with which such jets can be found in various portions of the country or at various times of the day.

The first portion of this study presents the results of an examination of two years of low-level wind data from 47 stations in the United States. Wind soundings were examined for the presence of strong wind maxima near the ground in an attempt to establish seasonal, diurnal, and geographical variations in the frequency of low-level jet observations.

The remainder of the study deals with the broad-scale features of the southerly low-level jet in the Great Plains: the horizontal and vertical structure of the jet during periods of strong southerly flow and its relationship to the geostrophic wind. Previous studies of the low-level jet in this area have generally involved special observational programs,[1] describing the time variations in the wind at a particular point in space, or, for a limited period of time, along a single line of stations.[2] This study examines the three-dimensional structure of the low-level jet through the standard network of radiosonde and rawinsonde stations. Detail is lost and time changes cannot be described adequately; however, it was felt that an examination of this type should be carried out before further detailed investigation is made through aircraft, tower, or special pilot balloon observations.

Low-level wind maxima are of interest not only as phenomena in themselves, but because of their effects upon weather and operations involving weather. Vertical wind shears associated with the low-level jet have been shown to constitute a significant hazard to jet aircraft on approach (Neyland, 1956). Byram (1954) has shown that the presence of a strong jet profile near the ground can greatly increase the rate of spreading of forest fires (see also Barad, 1962). Of greater meteorological interest, the southerly low-level jet across the south-central United States, is apparently related to the development of the thunderstorms over the Great Plains (see Petterssen 1956, Vol. 2). Diurnal oscillations in the speed of this jet are considered to be

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[1] See studies by Izumi (1964), Gerhardt (1962, 1963), and Jehn and Durie (1963), based on wind observations from the 1400 ft. Dallas tower.

[2] A special line of pilot balloon stations was set up in the Spring of 1961 at Wexler's instigation to study the low-level jet. Results are discussed by staff members, NSSP (1963) and Hoecker (1963).

responsible for the nighttime maximum in thunderstorm activity observed across a large portion of the midwest (see, for example, Sangster, 1958; Blackadar, 1959).

2. Explanation of the Jet

Before going into climatology of the low-level jet, a short summary will be given of several hypotheses that have been proposed to explain the occurrence of strong low-level wind maxima over the Great Plains.

Farquharson (1939) and Wagner (1939) explained the diurnal oscillation of the wind as a result of diurnal oscillations in the pressure and temperature fields. Wagner proposed that, over the central United States, these oscillations arise as a combined effect of the following circulations:

a. A circulation between the dry regions of the southwest and the surroundings.

b. A circulation between the continent and the ocean.

c. A circulation between the mountains and the plain.

According to Lettau (1954) and Blackadar (1955), low-level wind maxima forming at night in the central United States are not accompanied by increasing geostrophic winds and Blackadar (1957) has stated that these wind maxima are not produced by diurnal oscillations in the pressure fields. He has attempted to show that the jet profiles arise from an inertial oscillation of the ageostrophic wind vector as the air near the top of the friction layer is decoupled from the air below by the formation of a nocturnal inversion.

As stated in the introduction, this diurnal oscillation of the wind, taking place over a broad area, is thought to give rise to the large-scale southerly jet in the Great Plains.

Wexler (1961) has denied that the southerly jet in this area can be explained by the small-scale radiative and frictional effects alone. Reference must be made as well to the "...large-scale or bulk properties of the motion." According to Wexler, the jet, in this region, is formed as a result of the northward deflection by the Rocky Mountains of a shallow layer of air flowing westward across the Gulf of Mexico. Qualitatively, the increase in the Coriolis parameter as the air moves northward is offset by the development of strong anticyclonic shear within the current. Along the western boundary of the current, where the terrain elevations are higher, the air is retarded by friction. The two effects act together to produce a zone of maximum southerly wind at low levels along the eastern slopes of the Rocky Mountains.

The processes proposed by Blackadar and Wexler are not mutually exclusive and, according to Wexler, diurnal oscillations in the speed of the southerly jet are probably correctly explained by Blackadar.

Blackadar's argument is supported by calculations of wind oscillations arising from hypothetical time and altitude variations of the coefficient of eddy viscosity (Blackadar and Buajitta, 1957). Wexler has drawn a physical analogy between the southerly jet and the Gulf Stream (an analogy first suggested by Newton, 1959a). He has transposed numerical solutions for the Gulf Stream flow (Charney, 1955, and Morgan, 1956) to the case of the southerly jet, demonstrating an appreciably concentration of momentum along the eastern slopes of the Rocky Mountains.

3. Climatology

3.1 The Approach

The explanation of the jet by Blackadar implies that it is strictly a nighttime phenomenon; the explanation by Wexler, that it is bound to the eastern slopes of the Rocky Mountains. It seemed that the first phase of any further study of the jet should be to attempt to establish the extent to which strong low-level wind maxima are restricted to the region just east of the mountains and to determine the relative frequencies of jet observations on late afternoon and early morning wind soundings. To do this, a jet observation was defined, following Blackadar, as any significant, low-level, maximum in vertical profiles of the wind speed. An examination was then made of the frequencies of occurrence of such wind maxima at various stations in the United States.

3.2 Data Sources

A pilot study was carried out first using wind data from the 8 rawinsonde stations in Table 1. Each of these stations gives wind observations at six-hour intervals beginning at 00 GCT. Observations were examined for the one-year period from October, 1959 through September, 1960 using the Northern Hemisphere Data Tabulations published by the U. S. Weather Bureau.

Punched card wind data from 47 stations in the United States were then obtained for the two-year period from January, 1959 through December, 1960. Twice daily observations were used since the vast majority of stations in the United States take rawinsonde observations only at 00 GCT and 12 GCT. Punched cards were obtained from the National Weather Records Center at Asheville, North Carolina. Only the first card of each wind observation was requested, giving winds from the surface to

6000 m msl. Reporting levels in both the Northern Hemisphere Data Tabulations and in the punched card wind records are the same: Winds are given at the surface, at 150 and 300 m above the ground, in 500 m increments from 500 m to 3000 m msl and every 1000 m at higher levels. In all, approximately 70,000 punched cards were examined for low-level wind maxima using the IBM 7094 at the Computation Center of the University of Chicago.[3]

Table 1. Stations Used in the Pilot Study

Station	Elevation (meters)	Number of Observations
Montgomery, Ala.	61	1415
Fort Worth, Tex.	180	1445
Norfolk, Va.	9	1437
Dayton, Ohio	297	1439
Topeka, Kan.	267	1441
Portland, Maine	19	1340
International Falls, Minn.	360	1446
Seattle, Wash.	118	1438

Fig. 1 shows the location and the elevation of each of the stations used in the study. Stations within the Rocky Mountains were not used because of their high elevations, and because of the expected strong local effects due to mountain-valley wind systems.

[3]Computer time for this portion of the study was paid for by the National Science Foundation.

3.3 An Upper Boundary for the Jet

The first step in examining the wind soundings was to determine the highest level at which a wind maximum would be considered to be a low-level jet.

Blackadar (1957) referred to a significant wind maximum as one in which the wind reaches a maximum within the first 1.5 km above the ground and then decreases by at least 5 knots to the next higher minimum. A similar definition was used here; however, the upper boundary was set initially as the observation level nearest to 2.5 km above the ground at each station. The number of wind maxima at each level was then tabulated during the one-year period using wind data from the stations in Table 1. If the phenomenon were real, it was felt that there should be a sharp decrease in jet frequency somewhere within the first 2.5 km. The altitude at which this drop-off occurred could then serve as the upper limit in the definition of the jet.

Five levels only were considered at each station. Level 1 is the reporting level nearest to 500 m above the ground. Level 5 is the one closest to 2500 m above the ground.

Table 2 gives the vertical distribution of jet frequency at each of the 8 stations. Cases where jets were recorded at 2 or more levels were excluded from the tabulations. There is a maximum in frequency at level 1 or 2 at each station and a sharp drop-off in frequency between levels 2 and 3, or, at Fort Worth and Seattle, between levels 3 and 4. At the higher levels, there appears to be a completely random variation in frequency with jets about equally likely at any level.

The zone of relatively high jet frequency extends to between 1 and 1.5 km above the ground at each station. Therefore, 1.5 km above the ground was chosen as the highest level at which a wind maximum would be considered to be a low-level jet observation. Arakawa (1956) has referred to low-level jets at much higher levels (near 500 mb over Japan); however, the limit of 1.5 km includes the southerly Great Plains jet as it has been described by Means, Newton, Wexler, and others, and certainly includes the boundary-layer maximum described by Blackadar.

Blackadar's definition of a significant jet requires only that the speed at the level of maximum wind be at least 5 knots; however, the present study deals with strong wind maxima of the type normally associated with the southerly Great Plains jet and more restrictive speed criteria were therefore introduced for the machine analysis of the data.

Table 2. Vertical Distribution of Low-Level Wind Maxima. Percentage of the total that were observed at each level. Separation between levels is 500 m. Expected percentage in each box is 20 if jets are equally likely at all levels.

Level	Montgomery, Alabama	Fort Worth, Texas	Norfolk, Virginia	Dayton, Ohio	Topeka, Kansas	Portland, Maine	Int. Falls, Minnesota	Seattle, Washington
1	33.4	29.6	43.5	43.1	38.6	33.8	47.2	41.5
2	22.9	30.1	21.2	19.1	20.2	23.5	19.4	23.7
3	14.2	10.6	11.3	13.4	14.3	14.9	11.8	16.7
4	14.7	11.5	12.2	11.9	13.6	13.5	10.2	9.5
5	14.8	10.2	11.9	12.4	13.3	14.3	11.4	8.6
Total jets	718	955	858	620	893	704	706	750

3.4 Speed Criteria

Establishing a minimum speed and decrease in speed above the jet was primarily a subjective procedure. Some checking was done to make sure that seasonal geographical and diurnal distributions of wind maxima were not especially sensitive to the particular criteria selected, but the final selection was made by picking a reasonably stringent set of criteria which would still leave a large enough sample of jet observations to give some statistical validity to the study. A hierarchy of criteria were chosen:

Criterion 1: The wind at the level of maximum wind must equal or exceed 12 m sec^{-1} and must decrease by at least 6 m sec^{-1} to the next higher minimum or to the 3 km level, whichever is lower.

Criterion 2: The wind speed at the level of maximum wind must equal or exceed 16 m sec^{-1} and must decrease by at least 8 m sec^{-1} to the next higher minimum or to the 3 km level, whichever is lower.

Criterion 3: The wind speed at the level of maximum wind must equal or exceed 20 m sec^{-1} and must decrease by at least 10 m sec^{-1} to the next higher minimum, or to the 3 km level, whichever is lower.

Before starting the machine analysis of the data, the 8 stations in Table 1 were re-examined using all information levels and tabulating all wind maxima without regard to speed within the first 1.5 km above the ground. This criterion, similar to Blackadar's, will be referred to occasionally in this study as Criterion 0. Diurnal variations in speed, altitude, and frequency of occurrence of Criterion 0 jets are discussed in the appendix.

3.5 Geographical Distribution of Low-Level Wind Maxima

Figs. 2, 3, and 4 show the number of Criterion 1, 2, and 3 jet observations at each station during the two-year period from January, 1959 to December, 1960. Frequencies at stations along the west coast are listed in the lower right-hand corner of each map. Missing observations were handled by assigning, within each three-month period, the same percentage of jet observations as was observed on complete wind reports to the missing observations. All totaling and averaging procedures were carried out by machine.

The basic pattern in all three figures is the same. Regardless of the particular criterion selected, there is a pronounced maximum in frequency at 100 to 105 deg W on the Oklahoma-Kansas border. The zone of maximum frequency is roughly parallel to the Rocky Mountains and its location agrees closely with the position of the southerly jet as stated by Wexler. Between the Mississippi River and the Appalachian Mountains, the frequency of low-level jet observations drops off sharply so that in Fig. 4, for instance, Criterion 3 low-level wind maxima are observed in this region only a few times each year. On the west coast, strong jet observations are rare except at Seattle, Washington, where the frequencies are roughly equivalent to those in the eastern mid-west states.

A second but much weaker maximum in frequency is observed along the east coast. At Criterion 1 (Fig. 2) the frequency at Cape Hatteras is roughly 4/5 of that at Fort Worth; at Criterion 3, however, the ratio between the two frequencies drops to

1/3, indicating the disappearance of the east coast wind maxima as the criteria for a jet are made more and more stringent. Using Blackadar's criterion of a simple decrease in the winds of at least 3 m sec^{-1}, frequencies along the east coast almost match those in the Great Plains (see Table A1 in the Appendix).

Differences in frequency do exist at individual stations if the years 1959 and 1960 are considered separately; however, these differences are small and do not affect the overall geographical distributions shown in Figs. 2 through 4. The median absolute value of the difference in frequency between 1959 and 1960 at all 47 stations is 11 jet observations (Criterion 1).

3.6 Seasonal and Directional Breakdowns

Frequency distributions of Criterion 1 jet occurrence within 30 degree class intervals of wind direction are shown in Figs. 5 and 6. Where the wind speed maximum extended over two or more levels, the direction at the level of maximum wind was taken to be the average of the directions at the separate levels. The distributions are shown separately for winter and summer months (October through March and April through September, respectively) and seasonal totals are indicated for each station. The wind roses are plotted using actual numbers of jet observations within each class interval rather than probabilities at each station in order to show the preponderance of southerly wind maxima in the zone to the east of the Rocky Mountains over wind maxima in any other area.

At stations away from the Great Plains, a greater number of wind maxima were observed in winter than in summer. In the Great Plains, however, roughly 55 to 60 percent of all jet observations were found during the twelve summer months examined.

The wintertime directional breakdowns (Fig. 5) indicate a bi-modality in direction at most of the Great Plains stations. From Kansas southwards, southerly to southwesterly jets predominate. A secondary maximum in frequency from the north extends from North Dakota to Texas. The very large number of northerly maxima at Rapid City must be attributed to a local effect of the Black Hills, since it is not reflected at nearby stations. Northerly wind maxima in general were associated with cold frontal passages in which strong northerly winds near the ground were replaced by weak southerly flow above the top of the frontal surface.

They generally were not reported on successive observations at the same stations; they did, however, show a distinct early morning maximum in frequency,[4] indicating that diurnal oscillations of the wind must have an effect in producing or enhancing these northerly jets.

In the northeastern United States, most of the northwesterly wind maxima appear to be associated with the circulation around cyclones moving into the climatological Icelandic low. Kuettner (1959) has described such wind maxima in the New England area, pointing out that they typically occur with strong geostrophic winds at the ground and a pressure gradient which decreases sharply aloft due to the presence of a cold high to the west. Wind maxima may arise from a number of causes and it is not the intent of this study to examine the various kinds in any detail - only to point out that they exist.

Some geostrophic control over the wind maxima in all areas is suggested by the fact that the modal directions in all locations so closely approximate the streamlines of the mean geostrophic flow at sea level as indicated, for instance, by the mean sea level pressure chart for January given by Haurwitz and Austin (1944).

The dominance of southerly wind maxima across the Great Plains is much more pronounced in summer than in winter (compare Figs. 5 and 6). Modal wind directions from Brownsville to Omaha shift gradually from east-southeast to south-southwest indicative of the flow around the western boundary of the Bermuda High as it appears on mean sea level pressure charts for summer (Haurwitz and Austin, 1944) and of the general large-scale flow described by Wexler.

3.7 Relative Frequencies at 00 GCT and 12 GCT

For the two-year period as a whole, more than half of the Criterion 1 wind maxima were recorded on the morning (12 GCT) observation at 44 of the 47 stations considered.

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[4]For example, of 68 criterion 1 jets observed at Oklahoma City with direction from 330 deg to 060 deg, 42 occurred at 06 CST, 26 at 18 CST. The probability of this occurring by chance if jets were actually equally likely at either time is less than 5 percent. Corresponding figures at Amarillo, Texas are even more conclusive: 53 morning northerly jet observations to 17 at 18 CST.

The ratio:

$$r = \frac{\text{Jet observation at 12 GCT}}{\text{Total jet observations}} \times 100$$

is shown in Fig. 7 for winter and summer months separately.

The ratios are much less stable from year to year than are the overall frequencies (Fig. 2) and therefore less confidence can be placed in their reality. Several conclusions can be drawn, however:

1. Over most of the central and eastern United States, strong low-level wind maxima are much more likely to occur at 06 CST than at 18 CST.
2. Diurnal variations in frequency can be found during both summer and winter. The strength of the diurnal effect is more pronounced, however, during the summer months. (Note the difference in the areas covered by the 75 percent isopleth on summer and winter maps in Fig. 7).
3. The ratio between evening and morning jet frequencies is greatest at stations away from the coast line. There is some indication of a decrease in r along the Great Lakes as well.
4. There is a latitudinal variation in the strength of the diurnal effect. The maximum ratios do not follow the mountain contours as did the isopleths of overall frequency, but instead, spread out in a general west-southwest to east-northeast orientation with the zone of maximum frequency in both summer and winter at about 35 deg latitude.

Blackadar has suggested that diurnal oscillations should be greatest at inland stations where diurnal variations in the coefficient of eddy viscosity are larger than over the ocean. Furthermore, the observed latitudinal variation is predicted as part of the theory under the hypothesis that the amplitude of the diurnal oscillation of the wind will be greatest near 30 deg, where the period of an inertial oscillation is one day. At this latitude, the diurnal variation of the eddy viscosity, which presumably initiates the wind oscillation, will be in phase with the wind oscillation itself. An analogous situation occurs with the sea breeze where the most pronounced land-sea breezes have been observed at approximately 30 deg latitude (see Haurwitz, 1947).

Referring to Fig. 7, the ratios during the summer remain high as far north as International Falls, Minnesota. The region within the 75 percent isopleth extends over a range of approximately 10 deg of latitude, suggesting that synoptic effects or the presence of a broad area of relatively flat, smooth terrain may be of greater importance in producing a high frequency of nocturnal wind maxima than is the resonance phenomenon near 30 deg north.

Diurnal variations in frequency of occurrence and in speed and altitude of low-level wind maxima were examined on four-times-daily observations from the stations listed in Table 1 and this data is summarized in the Appendix.

In order to more-adequately describe the diurnal variations in jet frequency, a summary of the four-times-daily observations for Criterion 1 jets is given in Figs. 8 and 9. The graphs indicate the percentage of the total number of jet observations that occurred at each observation time.

While it is tempting to try to draw conclusions about the observed differences in frequency between midnight and 06 CST, these differences are probably not significant. At Portland, Maine, for example, the summertime maximum in jet frequency appears to occur between 18 CST and 00 CST. If an additional year of data is added, however, this trend reverses itself and a greater frequency of jet occurrence is found at 06 CST than at 18 CST (see Fig. 7). In the Great Plains, the time of maximum occurrence appears to shift from between 03 CST and 06 CST at Fort Worth to closer to midnight at Topeka and International Falls. This type of latitudinal shift in the time of the maximum wind should occur if Blackadar's hypothesis is correct, since the time of the wind maximum will be related to the period of an inertial oscillation:

$$T = 2\pi / f = \pi / \Omega \sin \phi$$

The rate of rotation of the ageostrophic wind vector is thus a function of the latitude. This rate at International Falls should be almost 1.5 times the rate at Fort Worth (periods for a complete rotation are 15.6 and 22.0 hours respectively). If, on the average, the onset time of the oscillation is the same at both stations, the time of maximum wind should be reached perhaps three hours earlier at International Falls than at Fort Worth. While this would appear to be the case on the wintertime charts, it is not so during the summer (Fig. 9).

4. The Southerly Jet in the Great Plains

In previous sections it was shown that the frequency of strong low-level wind maxima is much higher in a zone from northern Texas through Nebraska than in any other region of the country. Furthermore, the vast majority of jets in this region occur within a narrow range of wind directions at the level of maximum wind. The modal direction varies somewhat from station to station (Fig. 6), but at all stations it lies between south-southeast and south-west during the summer making it possible to sort out these southerly jet observations from the total in order to examine the frequency of occurrence of southerly wind maxima across the Great Plains.

A 90-deg range of wind directions was defined at each of 22 stations in the central United States and wind maxima with directions falling within this range were classified as southerly jet observations. The central angle was in general the modal class interval in Fig. 6 except that the greatest wind direction included was always less than 270 deg.

4.1 Frequency of Occurrence

Fig. 10 shows the geographical distribution of Criterion 1 southerly jet observations at 06 CST and 18 CST. The 06 CST chart shows a frequency maximum more than double the size of the maximum on the 18 CST map. The mere existence of a frequency maximum on the daytime charts indicates, however, that the southerly jet in this region is not totally a nocturnal phenomenon. The existence of this maximum and its southward displacement on the early morning chart is exactly what would be expected if the southerly jet in this area resulted from the combined effects of some basic flow pattern, present during the day as well as at night, and of a diurnal oscillation of the wind which reached maximum intensity at roughly 30 to 35 deg N.

The small-scale maximum at Brownsville extending towards Del Rio, Texas, is difficult to explain. It does not appear to be related to maxima further to the north. The probabilities of jet occurrence at Brownsville and at Oklahoma City are completely independent; thus, it is felt that analyzing two separate maxima in Fig. 11 is correct. The fact that the frequency maximum at Brownsville is observed on both morning and evening charts and that at both times the direction is from the south-southeast would seem to rule out any sea breeze effects.

Fig. 11 shows the frequencies of occurrence of Criterion 2 southerly wind maxima at 06 CST. Similar charts are not shown at 18 CST since all regularity to the patterns disappears on the evening charts. The frequencies of Criterion 3 wind maxima drops off very sharply on the evening observations as indicated by some representative comparisons in Table 3.

The low-level jet has long been considered a factor in the development of severe weather over the Midwest and it is interesting to compare the frequencies of jet occurrence with the regions of maximum thunderstorm and tornado occurrence.

Table 3. Criterion 3 Wind Maxima at 06 CST and 18 CST.

Station	Number of jet observations 06 CST	18 CST
Fort Worth, Texas	27	3
Oklahoma City, Oklahoma	43	11
Amarillo, Texas	48	4
Dodge City, Kansas	51	21
Omaha, Nebraska	24	12

Thom (1963) gives tornado probabilities in one-deg latitude and longitude areas based upon observations from 1953 to 1962. The center of greatest probability is in the middle of Oklahoma - within 50 miles of the position of the center of maximum southerly jet frequency in Fig. 11. While this does not imply that one phenomenon causes the other (it may well be that the same synoptic situation simply produces conditions favorable for low-level jet formation and for instability), a number of physical arguments have been advanced describing the jet as a cause of intense convection.

The various mechanisms relating the low-level jet to thunderstorm activity in the Midwest are summarized as follows:

a. The advection of warm, moist air at low levels and consequent destabilization of the air over large regions (Means, 1944, 1952).

b. The production of pressure jump lines by the impulsive addition of momentum beneath an inversion surface (Tepper, 1955).

c. Low-level convergence and the associated vertical velocity patterns (Bleeker and Andre, 1951; Blackadar, 1955, 1959; Sangster, 1958; Pitchford and London, 1962).

Most often, the low-level jet or the diurnal oscillation of the wind, which plays a role in producing the jet, has been cited as a cause of nocturnal thunderstorms over the Midwest.

Statistics compiled by the U. S. Hydrological Service covering the years 1906 to 1925 place the region of maximum nocturnal thunderstorm occurrence (as indicated by the frequency between 00 and 06 local time) in northeastern Kansas and western Iowa. This is north of the zone of maximum jet frequency in Fig. 11 but roughly along the axis of maximum frequency. Pitchford and London (1962) found a near coincidence between the mean axis of the low-level jet on 127 summer days and the line of maximum nocturnal thunderstorm occurrence. Bonner (1963) showed that rapid ascent of air on a synoptic scale can be expected downstream from the jet maximum and that this ascent may be an important factor in nocturnal thunderstorm occurrence. If this is true, the greatest frequency of nocturnal thunderstorms should be expected to occur somewhat north of the zone of maximum jet frequency as observed.

4.2 Speed and Altitude at the Level of Maximum Wind

Mean speeds and altitudes of the southerly jet observations were computed at each station at 18 CST and 06 CST separately.

Average speeds varied irregularly from station to station and it was impossible to draw any isotach pattern which could indicate the mean speed and intensity of the low-level jet. It had been anticipated that mean jet speeds would be higher on the morning than on the evening observations. This was not generally the case, however. At 12 of the 22 stations the reverse actually occurred.

Similarly, mean altitudes of the low-level wind maxima varied irregularly from station to station. Some of this irregularity is undoubtedly due to the variations in reporting levels at different stations because of the differences in station elevation. Mean altitudes at individual stations were significantly different on the 06 CST and

18 CST observations. At all stations except for Brownsville and Rapid City, the altitudes were lower at 06 CST than at 18 CST.

The overall mean of the altitudes of the 06 CST jet observations at all 22 stations was 785 m. The standard deviation among the individual stations was 127 m. If jet altitudes are translated to meters above sea level at each station, the standard deviation more than doubles, indicating that the jet does tend to occur at a constant level above the ground.

Of greater interest than the mean altitude is the actual distribution of wind maxima with height at individual stations. Continuous distributions have been estimated for Oklahoma City and Fort Worth (Fig. 12). Since the wind observation levels are irregularly spaced, a simple tabulation of jet frequency at each reporting level can give a misleading picture of the vertical distribution of jet observations. Furthermore, the differences in the reporting levels at individual stations makes comparison between stations difficult. To avoid these problems and to arrive at a continuous distribution function, probability density functions were constructed in the following way:

1. The number of jets at each reporting level was tabulated and it was assumed that the actual altitude of the wind maxima was somewhere within the range of altitudes bounded by half the distance to the neighboring observation levels.
2. Cumulative frequencies were computed using the midpoints between observation levels and then plotted as a function of altitude.
3. Smoothed cumulative frequency curves were drawn and then graphically differentiated to give the normalized probability curves.

In Fig. 12, the area is equivalent to the probability of observing a jet within a given range of altitude. At Oklahoma City, note that roughly one half of the southerly jets can be expected to occur within the narrow range of altitudes from about 350 to 650 meters above the ground. At Fort Worth, the same 50 percent appears to be spread out over the interval from about 600 to 1000 meters. Mean altitudes and altitude distributions indicate that most of the southerly wind maxima will be found well below the 850 mb level. Therefore, wind speeds and horizontal wind shears estimated from 850 mb charts will generally underestimate the strength and intensity of the jet.

The altitude data clearly show that southerly wind maxima in the Great Plains typically occur at heights too great to be picked up by observation towers such as the 1400 ft tower near Dallas. Furthermore, any statistics on relative frequencies of daytime and nighttime observations gathered from this tower data will be biased because of the greater altitude of the daytime jets which will only rarely be picked up by the tower measurements.

4.3 Seasonal Variations in Frequency of Occurrence

The summertime predominance of wind maxima over the Great Plains is somewhat more pronounced when only the southerly jets are considered. During the particular two-year period examined, August and September were the months of maximum southerly jet frequency. However, on the average, perhaps 30 percent of the southerly jet observations occurred during the winter months showing that the southerly jet is not entirely a summertime phenomenon. Two years of data is not enough to establish any definite seasonal trends other than the broad comparison between summer and winter; however, it is worth noting that the severe storm season in the Great Plains, April and May, is not the time of maximum jet activity.

5. Horizontal Structure of the Southerly Jet

The southerly jet has been shown to be a phenomenon which occurs with high frequency over the Great Plains during the morning hours. It is possible to gain some information about the jet from an examination of individual wind soundings; however, it is necessary to switch over to more subjective analysis techniques in order to describe the three-dimensional structure of the jet.

5.1 Low-Level Jet Coordinate System

A day-by-day machine summary was made of the 2 years of southerly jet observations in the Great Plains. Stations were categorized as 0 meaning no jet, 9 for missing or incomplete observations or 1, 2, or 3 corresponding to the jet criterion satisfied by the southerly jet observation. Since the purpose of the study was to examine the features of large-scale jets in the Great Plains, cases were selected where the greatest number of stations were reporting jets. In all, there were 116 days in which 6 or more of the 22 stations reported southerly jets on the 06 CST observations. By contrast, there were only 5 such days on the 18 CST observations, bringing out the complete dominance of the nighttime jet as a large-scale phenomenon. From the 116 morning jet days, 43 were selected as having one or more stations with Criterion 3 wind maxima and as complete as possible a set of wind observations.

Wind and temperature profiles at 06 CST from ground level to approximately 2.5 km above the ground were plotted for each of the 43 days. Wind speeds and directions were interpolated at 0.5 or 1.0 km above the ground and streamlines and isotachs were drawn for each of the days. The particular level analyzed was the one closest to the level of maximum wind at stations near the core of the jet. The purpose of this analysis was only to define the position of the isotach maximum and the axis of maximum wind, therefore, the particular level chosen was not too critical since there was little change in the position of the jet in an altitude change of 500 m.

In a number of cases, the analysis proved difficult because of apparently spurious observations or because of multiple wind maxima at a single level and these cases were simply discarded from the sample. The aim was to provide a number of cases where the position of the jet could be reliably determined without a great deal of subjective analysis. Twenty-eight cases were finally selected where there was a high degree of confidence in the position of the wind maximum. A coordinate system was set up in each case with its origin at the analyzed center of maximum wind and coordinate axes along and perpendicular to the axis of the jet. An example of a jet coordinate system is shown in Fig. 13. Krishnamurti (1961) has used the same type of coordinate system to describe mean properties of the Subtropical jet stream. Riehl and Fultz (1958) used a jet coordinate system in their analysis of laboratory jet streams.

At each day, the position of each reporting station in the jet coordinate system was recorded and plotted (see Fig. 13). Stations were not included where there was a front between the station and the southerly wind maximum or where it was impossible to pick out a level of maximum wind. Neither of these contingencies occurred too often, however. Of a total of 318 possible observations within the limits of the coordinate system as defined, 240 observations are included in the summaries to follow. The breakdown is given in Table 4.

Table 4. Wind Observations in Jet Coordinate System

	Discarded Observations			
Total Possible	Missing	Front	No Jet	Useable Obs.
318	22	13	43	240

In order to determine the average variations in the properties of the jet, along or near the level of maximum wind, speeds, temperatures and mixing ratios on individual observations were averaged within boxes, two coordinate units on a side. The 21 areas so defined and the number of available wind observations in each is shown in Fig. 14a. Distance in this coordinate system is conserved only along normals to the jet axis and along the axis itself. Thus, the boxes in Fig. 14 do not represent equal areas. However, the distortion is not extreme since, the curvature of the jet axis generally was small in the cases examined here.

Before discussing the mean patterns, it is worth noting the positions of the center of maximum wind in each of the 28 cases (Fig. 15). The median position of the centers is indicated by the 4-pointed star. This centroid is close to the center of maximum frequency of Criterion 3 jet observations (see Fig. 4). The shaded area indicates the region enclosed by the envelope of 26 of the 28 analyzed jet axes, showing that the jet typically occupies a fairly narrow range of positions in the south-central and central United States.

5.2 Twenty-eight Day Averages

Since the intensity of the jet varied from case to case, it was necessary to use a scaling factor in order to average the individual observations. Differences in wind speed between the speed at the level of maximum wind on the individual observation and the analyzed maximum speed at 0.5 or 1.0 km above the ground were tabulated and averaged within each box. These speed differences were later transformed to average wind speeds by adding to them the mean core velocity of the jet in the 28 cases. The results are shown in Fig. 14. In order to give a better picture of the scale of the low-level jet, average speeds are also shown in a schematic mean low-level jet coordinate system. In Fig. 16 the coordinate system has been centered at its median position and the axis is oriented roughly along the median jet axis (Fig. 15).

It is interesting to compare the longitudinal dimensions of the jet in Fig. 16 with theoretical dimensions of a velocity maximum. Newton (1959b) has suggested that the length of velocity streaks is related to the period of an inertial oscillation. Taking the simplest hypothesis, that the wind maximum derives from ageostrophic motions superimposed upon a roughly constant geostrophic flow, the time required for an air parcel to move between successive wind minima along the jet should adjust to the period of a free inertia oscillation (see Johannessen, 1956). In Fig. 16 we can estimate the length of the velocity streak to be slightly more than twice the distance between the center of maximum wind and the 16 m sec^{-1} isotach downstream, roughly 2,200 km. The air is moving through the isotach pattern at an average speed of perhaps 20 m sec^{-1} giving approximately 30 hours as the time required to pass through the zone of maximum wind. This is almost 1.5 times the period of an inertial oscillation at the mean latitude of the jet.

The longer period is to be expected if the jet is partly a reflection of the geostrophic wind field (Newton, 1959b); however, the physical explanation here should not be pressed too far since the calculations can only be considered to be correct in a very loose way because of the many approximations involved. In the case of the low-level jet, the wind field is far from persistent. As shown in preceeding sections, the jet tends to disappear during the day and to reform at night. Vertical motions of the air and variations in the frictional stress on individual parcels of air subject it to additional velocity perterbations so that it is difficult to describe the motion as the inertial oscillation of an air parcel moving freely through a steady state wind field.

Referring to Figs. 14b and c we can define typical regions of Criterion 1, 2, or 3 wind maxima by the mean speed at the level of maximum wind and the decrease to the next higher minimum. The number in parenthesis within each box in Fig. 14a indicates the criterion number which it satisfies. Criterion 1 is satisfied over a broad area of the jet whereas Criterion 3 is satisfied, on the average, only in the box nearest to the core of the jet and in adjacent boxes along the axis of the jet.

Fig. 14c gives the average value of the decrease in wind speed with height above the level of maximum wind. The greatest decrease in speed is observed along the axis of the jet and the decreases in general are somewhat higher on the upstream side of the wind maximum. Distances over which the speed decreases took place were not recorded but a typical separation between levels of maximum and minimum wind is of the order of 1 to 2 km. Taking 2 km in order to get a conservative estimate of the wind shear, the change in speed near the center of the jet is of the order of 7 m $sec^{-1}km^{-1}$ which, if geostrophic, would correspond to a horizontal temperature gradient of more than 2 deg per 100 km.

Fig. 16d shows that such temperature gradients do not exist, on the average, in the vicinity of the jet. Here, 850 mb temperatures were averaged in the jet coordinate system. Once again, it was necessary to scale the individual reports since cases were included from both summer and winter months and a chance extra proportion from one or the other in any box would make comparisons meaningless. The temperatures shown are the difference between the 850 mb temperature at the station and the analyzed 850 mb temperature at the center of the jet coordinates. Very little subjectivity was involved in determining this temperature since the jet position was usually very close to at least three reporting stations (see Fig. 15).

The temperature field at 850 mb does indicate a decrease in geostrophic wind speed with height along the axis of the jet. This decrease is strongest over and to the south of the center of maximum winds where the thermal wind is directed almost exactly opposite to the flow. However, the magnitude of the thermal wind shear is (using a mean temperature at the core of the jet) only about 1/3 or the required 7 m $sec^{-1}km^{-1}$.

It is interesting that the isotherms do not show a warm tongue along the axis of the jet but rather, high temperatures to the left of the jet with cold air to the right.

Mixing ratios, handled in the same way as the temperatures, are shown as well in Fig. 14d. While there was considerable scatter in the distribution of the mixing ratios, the general pattern follows roughly that of the temperature field, with a zone of relatively moist air to the left of the jet.

5.3 Relationship Between Jet Altitude and Inversion Height

Temperature and wind profiles were compared at 60 stations located near the core of the jet. Stations were selected from the 3 central boxes along the axis of the jet (Fig. 14a). The temperature inversion plays an important role in the explanation of the jet by Blackadar and the purpose here was to compare the altitudes of wind maxima and inversion surfaces near the core of the southerly jet.

Distinct inversions (actual increases of temperature with height) were found within the first 2.5 km above the ground on 52 of the 60 observations. In 21 cases, the analyzed level of maximum wind appeared to be above the top of the inversion, in 16 cases it was below. In the remaining 17 cases, inversion top and level of maximum wind coincided within plus or minus 50 meters.

The correlations coefficient between the level of maximum wind and height of the inversion surface in the 52 cases is .53, which is significantly different from 0 but which explains only a small fraction of the variance of the jet altitude about the mean. Most of the wind maxima were very pronounced so that there was little room for error in fixing the level of maximum wind. In the majority of the cases, inversions were not ground based but instead the base of the inversion was several hundred meters off the ground.

Blackadar (1957) has shown a strong correlation between inversion top and jet altitude using 88 selected cases from kite observations at Drexel, Nebraska. Cases were carefully chosen to represent conditions under which the major changes in the wind field could be expected to arise from the diurnal oscillation of the wind. In this study, cases were selected simply by their proximity to the core of the jet.

In view of the statistics on relative daytime-nighttime observations of the jet there is little doubt of the importance of the nocturnal increase in stability in producing the southerly jet. Therefore, the more uncertain relationship with the inversion surface cannot affect this argument. Apparently, however, by the time the jet is fully developed, in cases of strong southerly flow, it is impossible to establish any powerful relationship between the inversion top and the level of maximum wind.

5.4 Comments on Maximum Speeds in the Jet

An interesting feature of the wind speeds at the core of the jet is that there appears to be a natural cut-off point in the wind velocity at speeds between 55 and 60 knots. It seems to be no accident that cross sections by Wexler of a southerly low-level jet show a maximum speed of 55 knots on each of two mornings; that on the cross sections by Hoecker using the special network of soundings three out of three morning cross sections give a maximum jet speed of 55 knots; that an example of a boundary layer jet by Blackadar (1957) shows a speed of 53 knots. Of the 43 cases initially analyzed here before the reduction to the 28 used in the study described, the wind speed analyzed at the core of the jet exceeded 60 knots on only four occasions. The maximum speed was between 50 and 60 knots on 30 of the 43 occurrences.

Of the 4 cases with speeds exceeding 60 knots, two occurred in April, one in December and one in June. The spring and summer cases occurred with fronts moving into the region; the two cases in December with an intense high cell over the eastern United States. The common feature in all four was an unusually strong pressure gradient across the Great Plains.

5.5 Wind Shear Along the Level of Maximum Wind

Fig. 17 shows the decrease in wind speed normal to the jet. The plotted x's indicate the difference between observed wind and analyzed maximum wind at stations located within Boxes J, K, and L, in Fig. 14a. That is, from stations located within 150 km of the normal to the jet, through the center of maximum winds. Regression lines through the origin were computed on both cyclonic and anticyclonic sides of the jet, yielding a slope of $0.37 \times 10^{-4} sec^{-1}$ on the anticyclonic side, slightly less than the cyclonic shear indicated to the left of the jet. Dashed lines on both sides indicate extreme values of the shear, neglecting points clustered near the core of the jet since, near the center, longitudinal displacements could have a significant effect on the observed differences in wind speed. Apparently, observed anticyclonic wind shears at the level of maximum wind do not approach the value of the Coriolis parameter at the latitude of the jet as they frequently do in the case of the higher level jet streams (Reiter 1963). Estimates of the wind shear along constant pressure surfaces may, however, give much higher values than indicated here because of the considerable vertical wind shear above and below the level of maximum wind. Measurements of the horizontal component of wind shear are discussed in a later section.

The ratio $V\ max/\ V$, on a logarithmic scale, vs distance from the jet axis, is shown in Fig. 18. Included is a similar graph by Reiter (1963) constructed from observations near the polar tropospheric jet. Curves for the low-level jet stream were constructed by eye whereas Reiter managed to fit the data for the high level jet into an exponential relationship, giving a straight line on the semi-log graph. The difference in scale between the two jet systems is not as great as might have been supposed. The half-power point for the low-level jet curve occurs at 300 to 350 km on both sides of the jet axis. On Reiter's diagram half-power points occur at 450 to 500 km on the cyclonic side of the jet and approximately 800 km on the anticyclonic side. Roughly, the ratio in dimensions normal to the axis of the jet is two to one.

6. Comparison of Geostrophic and Observed Winds

Means (1954) showed that a core of maximum geostrophic wind can exist on cross sections through the Great Plains; however, the explanation of the jet by Blackadar and comparisons of geostrophic and ageostrophic winds on individual soundings have indicated that the southerly jet may be almost entirely the result of ageostrophic components of the wind. The purpose of this section is to examine the amount of geostrophic control of the wind field in the southerly low-level jet.

6.1 Method

Since the southerly low-level jet stream in the great plains is typically found in regions where terrain elevations range from roughly 200 m to more than 1500 m above sea level (Fig. 15), geostrophic winds near the jet cannot be accurately determined from the sea-level pressure field alone. The difficulty in obtaining reliable estimates of the geostrophic wind over sloping terrain is well known and a number of methods have been proposed to minimize the errors in its determination. Among these are methods by Bellamy (1954), Sangster (1960), and Fujita and Brown (1957). The approach used here is essentially that developed by Fujita and Brown.

We assume that the thermal wind shear is a constant vector from sea level to 5000 ft msl at any particular location. In this case, the geostrophic wind $\mathbb{V}_g$ at any level $h \leqslant 5000$ ft is given by

$$(\mathbb{V}_g)_h = (\mathbb{V}_g)_o + \frac{h}{5000}\left[(\mathbb{V}_g)_{5000} - (\mathbb{V}_g)_o\right]. \qquad (1)$$

Thus, as the terrain elevation approaches 5000 ft, more and more weight is given to the 5000-ft chart in determining the geostrophic wind at the level of the terrain. Fujita (1962) has shown that time-averaged geostrophic winds computed from this assumption agree much more closely with observed winds averaged over the same time period than do those computed from the sea-level pressure fields alone.

In practice, geostrophic and thermal winds were determined from constant pressure charts since the thermal wind equation is much simpler to evaluate in (x, y, p, t) coordinates.

From the 28 cases discussed in the previous section 10 were selected for the comparison of geostrophic and observed winds near the level of maximum wind. Cases were selected where there was no cold front close enough to the jet axis to introduce northerly components into the wind field at any of the coordinate points and where the level of maximum wind was near 500 m so that a standard elevation of 500 m plus the terrain elevation could be used in computing the geostrophic wind. Elevations were taken from the mean terrain map prepared by McClain (1960)[5].

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[5] McClain averaged the elevations determined from aeronautical charts over 1/4 deg latitude-longitude areas and then smoothed the resulting elevations to obtain a smoothed representation of the terrain. In the present study, unsmoothed original averages were used to give the terrain elevation at grid points in the jet coordinate system in each of the 10 cases.

Where the height, terrain plus 500 m, exceeded 1500 m, which happened frequently along the western boundary of the jet, the thermal wind was computed between the 850 and 700 mb levels. The same linear relationship (equation 1) was assumed to hold, with subscript 0 referring to the 850-mb level.

Since the comparison between observed and geostrophic winds is difficult under the best of circumstances, the procedure followed will be described in some detail:

1. Sea level pressures were analyzed at one-mb intervals to give a fairly smooth pattern over the central United States. An attempt was made to determine the excess pressure in the vicinity of thunderstorm systems, where these occurred (Fujita, 1962) in order to determine the "undisturbed" pressure field.
2. Eight-hundred fifty mb charts were analyzed at contour intervals of 10 meters.
3. Sea-level pressures were converted to 1000 mb heights using a conversion factor determined in each case from the mean surface temperatures in the vicinity of the low-level jet.
4. Thickness charts were made and smoothed and 850 mb and 1000 mb charts were adjusted to fit the smoothed thickness patterns.

   In this way, height fields were made as vertically consistent as possible. Winds were used in the contour analysis only at 850 mb (and at 700 mb when necessary) and then only as a guide. No geostrophic wind scale was used in the analysis so that geostrophic and observed winds can be considered to be independently determined. Wind and pressure analyses were carried out several weeks apart and no reference was made to the previous jet analysis when analyzing the pressure and height fields.
5. The jet coordinate system for each case was placed as an overlay on the 1000 mb and thickness charts. Geostrophic and thermal winds were computed at the coordinate points. Altitudes of the particular coordinates had been determined previously. Equation (1) was then solved graphically to give the geostrophic wind 500 m above the level of the terrain at 30 coordinate points in each of the 10 cases.
6. Geostrophic winds were plotted and smoothed under the assumption that random errors would naturally arise from the many separate steps in the calculations. Almost no smoothing was required, however. In all cases, smoothed grid point values of the geostrophic wind were

within 1 m sec^{-1} in speed and 10 deg in direction of the originally computed values.

7. Actual winds at each coordinate point were determined from the streamline and isotach analyses at the 500 m level. These, along with the geostrophic wind and the orientation of the coordinate axes at each point were entered on punched cards. Winds were broken into components in the jet coordinate system. The ageostrophic winds were then computed at each point and expressed, by two coordinate rotations, in three coordinate systems for easy reference. The first was simply the (s, n) jet system; the second gave components along and perpendicular to the geostrophic wind; the third expressed components with respect to the direction of the actual wind. The components at each point were printed out for each case as were average values at each of the coordinate points for all ten cases. Components were plotted and analyzed in each of the separate cases but only the average data will be shown.

6.2 Synoptic Characteristics of the 10 Cases Examined

The surface charts at 06 CST are shown in Fig. 19. Frontal systems and present weather have been entered as well. The shaded areas give the position of the low-level jet at 500 m above the terrain as indicated by the 20 m sec^{-1} isotach. Darker shading is used to indicate the regions of 25 or 30 m sec^{-1} winds where these exist. There are marked differences in the tightness of the pressure gradient across the south-central United States (compare, for example, 19 April, 1960 with 10 July, 1960); however, the patterns are similar, with high pressure across the eastern or south eastern United States and a front, trough or low to the left of the jet acting together to produce a regular, generally anticyclonically curving flow of air northward from the Gulf of Mexico. In some cases the wind maxima appear to spread out downstream from the core along a zone of tight pressure gradient (see 2 December, 1960); in other cases, the wind streak is effectively chopped off downstream by the presence of a trough or warm front (14 July, 1959 and 10 July, 1960). With the possible exception of 14 July, 1959, there was no obvious relationship between thunderstorm activity and the position of the jet. On the contrary, the thunderstorms appeared to be primarily frontal or coastal storms.

6.3 Results

Unless otherwise indicated, U and V components refer to the jet coordinate system (Fig. 13). Fig. 20 shows the 10 case averages of the V component (component along the axis of the jet) of the observed 500 m wind in the jet coordinate system. The pattern is very much like that obtained from the individual station data in the preceeding chapter (Fig. 14b). The average speed of the jet maximum at 500 meters (including the U component) is 26.6 m sec^{-1}. Shears to the left and right of the jet are roughly 0.5 and $0.4 \times 10^{-4} sec^{-1}$, respectively, only slightly greater than the slope of the regression lines in Fig. 17.

The mean V component of the geostrophic wind at 500 m for the 10 days is shown in Fig. 21. On the average, and in each of the 10 individual cases, there is a distinct wind maximum in the geostrophic wind field. The strength of this maximum varies between 10 m sec^{-1} and 26 m sec^{-1} in individual cases and the variation of this speed shows a fairly good correlation (0.7) with the actual speed of the jet. Thus, approximately 50% of the variance of the wind speed maxima in individual cases is explained by variations in the speed of the geostrophic wind. The patterns of geostrophic and observed V components are similar. The spatial correlation at the 30 grid points between the geostrophic and observed winds is .81, which means that both the structure and the strength of the actual winds in the jet are strongly related to the geostrophic wind field. While the original paper by Means pointed to the jet as a geostrophic phenomenon, during recent years the tendency has been to consider that the jet could be explained simply by diurnal oscillation of the ageostrophic wind (see Blackadar and Buajitta, 1959).

The existence of a jet in the geostrophic wind field gives an explanation for the fact that daytime wind maxima are observed over the Great Plains (see Fig. 10). In this connection, the displacement of the geostrophic maximum to the north of the maxima in the observed winds is almost exactly the same as the morning-evening displacement of the frequency maximum in Fig. 10.

The ratio of actual to geostrophic wind (V / V_g) at the core of the jet has an average value of 1.7 and varies from a minimum of 1.2 to a maximum of 3.4. In this latter case, however, (10 July, 1960, see Fig. 19) the jet is strongly curved anticyclonically, giving a cyclostrophic correction to the geostrophic wind of roughly 5 m sec^{-1}. Using the gradient wind instead of the geostrophic wind, the ratio reduces to 2.1 . In other cases, the flow was nearly straight and gradient corrections are no larger than 1 to 2 m sec^{-1}.

Fig. 22 gives the average V component of the ageostrophic wind. As might be expected, the ageostrophic flow is a maximum at the core of the jet, and with the exception of one point, along the axis of the jet. The U components are not plotted, however, they are listed for both geostrophic and observed winds in Table 5. Grid points in the table are numbered in matrix form with the number in the one's location referring to row position, the decimal number referring to the column. For example, the upper left hand point in Fig. 22 is grid point 0.1. Grid point 2.3 is the center of the jet coordinate system. The U components of the ageostrophic wind are (Table 5, column 6) much smaller than the component along the axis of the jet. The ageostrophic flow is directed, almost everywhere, to the left of the jet axis. Columns 8 and 9 in Table 5 give the components of the ageostrophic wind along and perpendicular to the observed wind. (U^* is positive to the right of the observed wind, V^* is plus when the ageostrophic component is directed along the flow). At all grid points except the two in the upper left hand corner of the jet (see Fig. 22) the ageostrophic wind is directed to the left of the actual wind. The magnitude of this component is a maximum along normals through and to the south of the core of maximum winds.

The consistency of the (U^*, V^*) averages is indicated in columns 10 and 11 which list the number of times from a possible 10 that the ageostrophic wind is directed to the left of the actual wind ($U^* < 0$) and, in column 11, the number of times that the ageostrophic flow has a component in the direction of the wind. Components with respect to the geostrophic wind are not shown; however, the U^* component with respect to the geostrophic wind has the same sign at each point but slightly greater magnitude. Thus, the flow is consistently towards low pressure indicating, at this time, production of kinetic energy through the work done by the pressure forces throughout the region of the jet[6].

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[6] An expression for the local change of kinetic energy per unit mass is given below:

$$\frac{\partial}{\partial t}(\mathrm{k.e.}) = -\mathbb{V}\cdot\nabla(\mathrm{k.e.}) - \mathbb{V}\cdot w\frac{\partial \mathbb{V}}{\partial Z} + f\,\mathbb{V}_g\cdot\mathbb{V}'\times\mathbb{k} + \mathbb{V}\cdot\mathbb{F}$$

where $\mathbb{F}$ is the frictional force per unit mass.

The production of kinetic energy by cross-isobaric flow is proportional to the product of the geostrophic wind and the component of the ageostrophic wind perpendicular to it. The maximum observed production of kinetic energy occurs at the center of the jet and is sufficient to balance a frictional dissipation, or to produce kinetic energy, at the rate of approximately 16 $m^2\ sec^{-2}$ per hr.

The low-level jet is far from a steady state system, however, and there is little justification for attempting to evaluate the various terms in this equation unless it could be done at time intervals of the order of 3 hours or less.

Table 5: Summary of average wind components and accelerations in jet coordinate system. Determinations of geostrophic and ageostrophic winds were made at 500 m above the ground in ten cases and components were averaged at the coordinate points listed. See Fig. 20 and text for location of points. An asterisk means axes along and perpendicular to the real wind.

Grid point	Geostrophic Wind		Real Wind		Ageostrophic Wind		Ageostrophic Wind		Times	Times	θ
	Ug	Vg	U	V	U	V	U*	V*	U* < 0	V* > 0	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
0.1	-1.7	8.4	-0.1	9.4	1.6	0.9	1.5	0.8	4	6	11
0.2	-1.5	12.8	-0.8	15.5	0.7	2.6	0.6	2.4	5	8	18
0.3	-1.2	14.4	-1.6	19.1	-0.4	4.7	-0.3	4.7	6	9	30
0.4	-0.8	12.4	-1.7	16.4	-1.0	4.1	-0.6	4.1	8	10	30
0.5	-0.8	9.6	-1.3	11.9	-0.5	2.2	-0.3	2.4	6	8	24
0.6	-1.0	7.3	-0.7	8.1	0.3	0.9	-0.1	1.4	5	7	20
1.1	-0.9	10.1	-1.2	10.2	-0.3	0.2	-0.6	0.7	7	7	8
1.2	-1.2	14.4	-2.0	17.7	-0.9	3.3	-0.4	3.6	7	8	24
1.3	-1.6	16.8	-3.9	22.4	-2.3	5.6	-1.1	6.0	9	10	32
1.4	-2.2	14.5	-4.2	18.4	-2.0	3.9	-1.2	4.5	9	9	29
1.5	-1.9	11.2	-4.1	13.0	-2.2	1.8	-1.7	2.8	8	10	26
1.6	-1.9	8.3	-3.2	8.6	-1.4	0.3	-1.3	1.7	5	9	24
2.1	3.4	9.5	1.2	11.3	-2.2	1.7	-2.4	2.1	8	6	23
2.2	1.8	13.5	-0.4	19.0	-2.2	5.5	-2.1	5.6	8	10	35
2.3	0.2	15.7	-2.8	26.0	-3.0	10.4	-1.6	10.9	7	10	50
2.4	-1.7	14.4	-5.5	19.3	-3.9	4.9	-2.3	6.0	10	10	37
2.5	-2.4	11.7	-4.5	13.7	-2.1	2.0	-1.3	2.8	7	10	24
2.6	-2.7	8.7	-3.9	8.9	-1.3	0.1	-1.3	1.3	7	8	18
3.1	5.0	5.2	2.9	10.7	-2.2	5.5	-3.6	4.9	9	10	55
3.2	3.6	3.6	2.2	17.7	-1.4	8.0	-2.3	7.9	7	10	54
3.3	1.8	12.7	-0.4	21.6	-2.2	8.8	-1.7	8.9	10	10	49
3.4	-0.3	13.0	-3.2	18.1	-2.9	5.1	-1.9	5.7	9	9	37
3.5	-1.3	11.0	-3.3	13.8	-2.0	2.8	-1.6	3.5	7	10	30
3.6	-1.9	8.4	-2.8	8.7	-0.8	0.3	-1.1	1.1	7	8	16
4.1	3.3	3.3	2.6	9.6	-0.7	6.2	-2.2	6.5	8	10	82
4.2	2.9	6.5	2.1	14.2	-0.8	7.7	-1.8	7.7	8	10	65
4.3	1.9	9.5	-0.4	16.7	-2.4	7.2	-2.1	7.4	6	10	53
4.4	0.2	11.8	-2.9	14.9	-3.1	3.1	-2.8	3.8	9	8	31
4.5	-0.9	9.8	-3.0	11.0	-2.1	1.2	-2.0	2.3	7	10	25
4.6	-1.5	7.8	-2.9	7.5	-1.4	-0.3	-1.6	1.3	5	9	20

Neglecting friction, the horizontal momentum equation may be written (Haltiner and Martin, 1957)

$$\frac{d\mathbb{V}}{dt} = f\,\mathbb{V}' \times \mathbb{k} \qquad (2)$$

where $\mathbb{V}'$ refers to the ageostrophic wind. The acceleration of the wind is therefore a vector directed 90 deg to the right of the ageostrophic wind, with magnitude $f\,|\mathbb{V}'|$. In Table 5, U^* implies an acceleration along the flow, V^* an acceleration perpendicular to it. From Column 8, Table 5, there is a component of the acceleration directed along the motion at almost all points of the jet. The acceleration is a maximum upstream from the jet axis and, in this region, balances fairly well the observed increase in the speed of a parcel moving into the jet maximum (see Fig. 20). The major component of the ageostrophic wind, however, is directed along the actual wind (Column 9) indicating that most of the wind acceleration through the jet occurs in a direction normal to the wind, contributing to a rotation with little change in speed, of the observed winds.

A rough-scale analysis of the convective accelerations in the vicinity of the jet leads to the following conclusions:

1. Ageostrophic winds from accelerations due to horizontal motions through the isotach pattern in Fig. 20 do not exceed 2 m sec^{-1}.
2. Ageostrophic winds from accelerations due to vertical displacements are generally less than 2 m sec^{-1} but may reach 3 m sec^{-1} downstream from the jet maximum.
3. Therefore, assuming friction to be unimportant at the 500 m level at night, the local acceleration of the wind must provide the primary contribution to the observed ageostrophic winds in the vicinity of the jet.

We can test the magnitude of this acceleration by assuming that it remains perpendicular to the wind and constant in magnitude over a 6-hr period and then solving for the resulting rotation of the wind. The magnitude of the change in velocity ΔV is, from equation 2,

$$\Delta V = f\,V\Delta t \equiv V\theta$$

where V and V' are the speeds of the actual and ageostrophic winds respectively and θ is the angular rotation of V during the time Δt. The predicted 6-hr rotation at each grid point is given in Table 5, column 12. With some exceptions near the lower left hand boundary of the jets where the confidence in the ageostrophic wind is lowest, the ageostrophic components appear to give a reasonable rotation rate in view of the many simplifying assumptions. In a case study of a strong low-level jet (Bonner, 1963) a nearly uniform turning of the wind was observed during the period 00 to 06 CST with an average 6-hr rotation of 20 to 30 deg, which agrees reasonably well with the values in column 12. This simply shows that even if the entire measured acceleration is assumed to go into a local turning of the wind, the results are not unreasonable.

Referring again to Fig. 22, the anticyclonic shear of the ageostrophic wind along the coordinate axis normal to the jet is -8 m sec^{-1} in 300 km or $0.27 \times 10^{-4} sec^{-1}$ - exactly twice the indicated anticyclonic shear of the geostrophic wind (Fig. 21). On the cyclonic flank of the jet, the major portion of the shear again arises from the ageostrophic wind.

Vorticity fields in the vicinity of the jet can therefore be expected to result primarily from the ageostrophic wind field. Divergence and resulting vertical motion patterns are necessarily dependent upon the ageostrophic wind.

An estimate of the mean divergence at the 500 m level can be obtained from the downstream change in the V component of the ageostrophic wind along the axis of the jet. Krishnamurti (1961) has developed an expression for the divergence in a curvilinear jet coordinate system which could, with some approximations, be applied to the mean data presented here; however, since the mean curvature of the jet axis was small, we can get an order of magnitude estimate, at least, by simply subtracting ageostrophic components along the jet axis, which yields on the downstream side, a mean convergence of 1 to $2 \times 10^{-5} sec^{-1}$. According to Petterssen (1956a) this amount of convergence is typical of medium to intense synoptic-scale disturbances. If we assume that this convergence is an average value within the first 1500 m, the corresponding vertical velocity at 1500 m above the ground is 1.5 to 3 cm sec^{-1} (assuming w=0 at the ground).

7. Mean Cross Sections Through the Jet

The wind analysis in the 10 cases discussed in the previous section was extended to the surface and to levels 1.0, 1.5, and 2.0 km above the terrain. The surface winds were taken from the surface synoptic data; winds aloft were interpolated from the previously plotted curves of wind as a function of height above the station. Streamlines and isotachs were drawn and the wind speed and direction at grid points in the jet coordinate system were tabulated and entered on punched cards. Winds at each point were then broken down into components along and perpendicular to the jet. The machine was programmed to print out the wind components at each of the 4 levels, in each case, as well as the overall averages for all 10 cases. Wind components at 500 m were obtained from the calculations in the previous section. The printout of the individual cases was intended to serve as a means of checking the significance of the averaged data and only the average cross sections will be shown.

7.1 Observed Winds

Fig. 23 gives the average components along and perpendicular to the jet axis along a section normal to the jet, through the center of maximum wind. The jet core apparently extends, on the average, to only about 2 km above the ground, which for typical terrain elevations in this region implies that it would be only weakly reflected, if at all, on 700 mb charts. Directional changes through the jet are slow and gradual as indicated by the vertical variation of the U component with height.

The U component indicates radial inflow on both sides of the jet. In sections taken upstream from the center of maximum wind (not shown) roughly the same inflow patterns were found. In this upstream region, the resulting accumulation of mass can at least partially be accounted for by an increased removal of air along the streamlines moving into the jet core. The persistence of this inflow at the jet core implies, however, (neglecting density changes) that the air must be removed through vertical motions. In a case study of a low-level jet stream (Bonner, 1963) pronounced vertical motions are found downstream from the center of maximum wind as indicated here by a rough estimation of the mass continuity requirements.

7.2 Mean Horizontal and Vertical Wind Shears

Wind shear measured along the coordinate surfaces in Fig. 23 can be converted to horizontal wind shear by the following relationship:

$$\frac{\partial V}{\partial n} = \frac{\delta V}{\delta n} - \frac{\partial V}{\partial Z}\frac{\delta Z}{\delta n} \qquad (3)$$

where $\partial V/\partial n$ is the shear of the V component of the wind measured at constant height above sea level: δV is the velocity difference at constant height above the terrain and $\partial V/\partial Z$ is the vertical wind shear. $\delta Z/\delta n$ is the slope of the terrain, which must be determined at each coordinate point in each of the 10 cases. The slope was computed from the mean terrain map by McClain, mentioned earlier. Cross sections were analyzed for each of the 10 cases and values were interpolated at height intervals of 250 m and horizontal intervals of 75 km. The slope, and the V component of the wind at each point were entered on punched cards and the following calculations were made:

1. Vertical wind shear at each interior point.
2. The shear at constant height above the terrain.
3. By solving equation (3), the horizontal wind shear.

This was done for each case separately and the results were averaged for all 10 cases. Tables of mean values of the 3 shears and of standard deviations of each were printed out by the machine. The 10 case averages in the vertical and horizontal wind shear are shown in Figs. 24 and 25.

The vertical wind shear is expressed in terms of m sec^{-1} per km. Greatest vertical shears are found within the friction layer, beneath the core of the jet. The average negative shear above the center of the jet is 15 m $sec^{-1}km^{-1}$. In individual cases this value was as large as 21 m sec^{-1}; the standard deviation of the vertical shear at this point of maximum decrease was 4.2 m $sec^{-1}km^{-1}$.

In Fig. 25, the horizontal wind shear is not 0 at the axis of the jet because of the terrain slope and the large vertical shear within the friction layer (see equation 3). Neglecting curvature effects, Fig. 25 is a representation of the relative vorticity patterns near the low-level jet. On the cyclonic flank, the absolute vorticity approaches 2f below the level of the jet. The standard deviation at the point of maximum cyclonic shear is $.29 \times 10^{-4} sec^{-1}$. To the right of the jet, the absolute vorticity is definitely greater than 0. The standard deviation at the point of maximum anticyclonic relative vorticity is only $.09 \times 10^{-4} sec^{-1}$; therefore, to reach the zero point of absolute vorticity would require a relative vorticity approximately 4 sigma away from the mean of the 10 cases. Zero absolute vorticity to the right of the polar front jet is typical (Reiter, 1963). Newton and Palmen (1948) have shown that the geostrophic wind shear leads to approximately 0 absolute vorticity, which has implications regarding the dynamic stability of the motion. In the case of the low-level jet stream, 0 absolute vorticity is not approached in the actual winds and certainly not in the geostrophic wind field.

8. Summary and Conclusions

The southerly low-level jet has been isolated as a phenomenon occurring within the first 1000 to 1500 m above the ground in the south-central United States. Similar wind maxima are observed throughout the United States; however, the frequency of occurrence of the southerly jet in the Great Plains is not approached by that of low-level wind maxima in any other area. The large-scale southerly jet has been shown to be primarily a nighttime feature. The stronger the criterion is made for a jet, the greater the ratio between nighttime and daytime southerly jet occurrence. If the criteria are extended to include simultaneous jet occurrences at a large number of stations, the daytime jet practically disappears. Strong early morning southerly jets occur most often in late summer and again in the spring; however, they may appear at any time of the year. Synoptic conditions which favor large-scale jet formation are those which contribute to a tight pressure gradient across the Great Plains with a smooth uninterrupted flow of air northward from the Gulf of Mexico.

The hypothesis which best fits the data presented is that stated by Wexler: the large-scale nocturnal southerly jets arise from the superposition of a diurnal oscillation of the boundary layer winds upon broad scale synoptic characteristics of the flow. The diurnal oscillation of the wind is real (see appendix) there is still some doubt, however, about its cause. For example, a more recent study by Hering and Borden (1962) has indicated a connection between the diurnal oscillation in the boundary layer and diurnal oscillations at 5 km.

The regions, altitudes, times, synoptic conditions and to some extent, the seasons for strong southerly jet formation have been examined here and data from the study should be useful in planning future operations dealing with the low-level jet. Further detailed examination of the low-level jet should provide for observations close together in time and in space so that time changes of the wind over large regions of the jet could be examined. It might then be possible through careful analysis to measure the various accelerations resulting in the ageostrophic winds in order to determine what factors would have to be included in more sophisticated models of the jet.

Acknowledgements:

I wish to thank Professor S. Petterssen for his encouragement and advice, and Mrs. G. Baralt for her assistance in programming and in hand calculation of some of the data presented here.

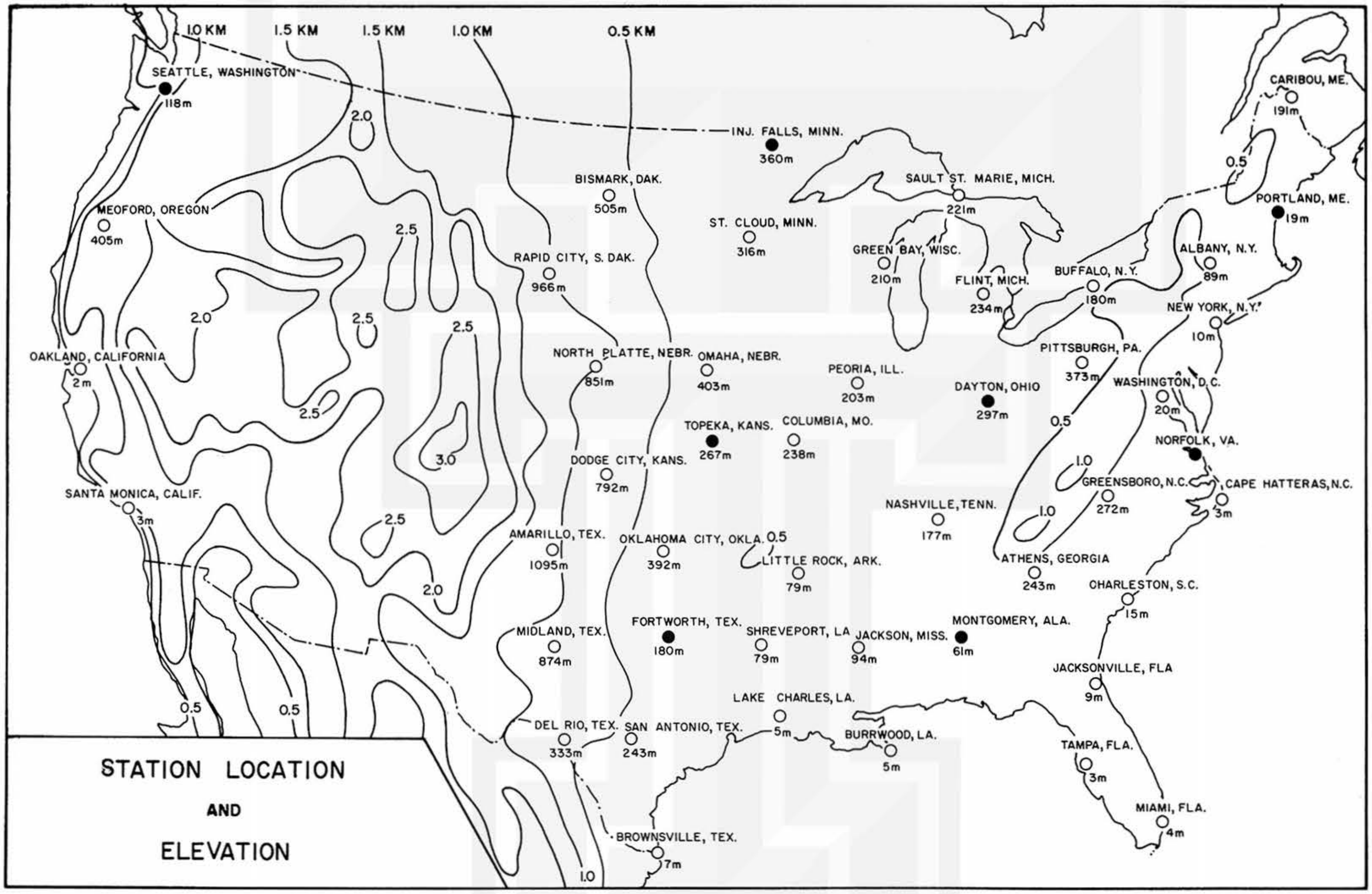

Fig. 1. Stations used in the machine search for low-level jet observations. Station elevations are given in meters above sea level. Black circles indicate stations at which four-times daily wind observations were examined for a one-year period.

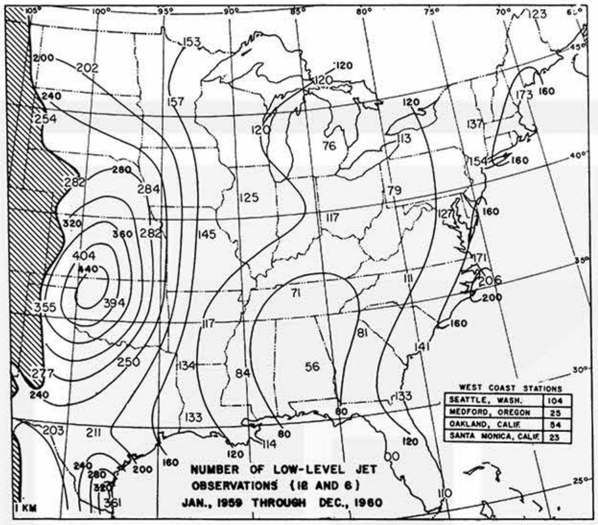

Fig. 2. Number of Criterion 1 low-level jet observations from January 1959 through December 1960. 18 CST and 06 CST combined.

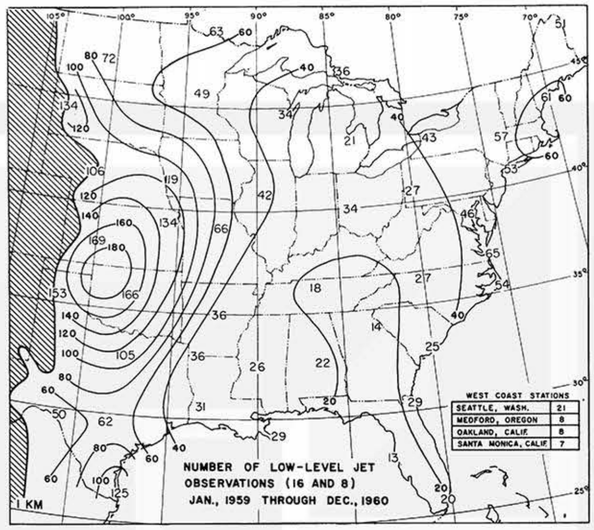

Fig. 3. Same as Fig. 2 except Criterion 2.

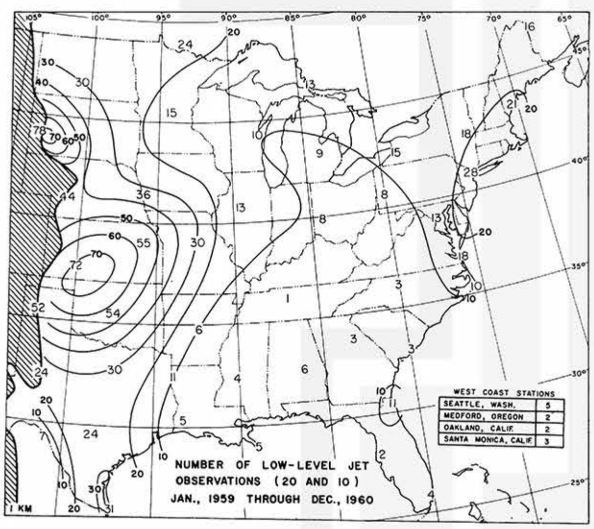

Fig. 4. Same as Fig. 3 except Criterion 3.

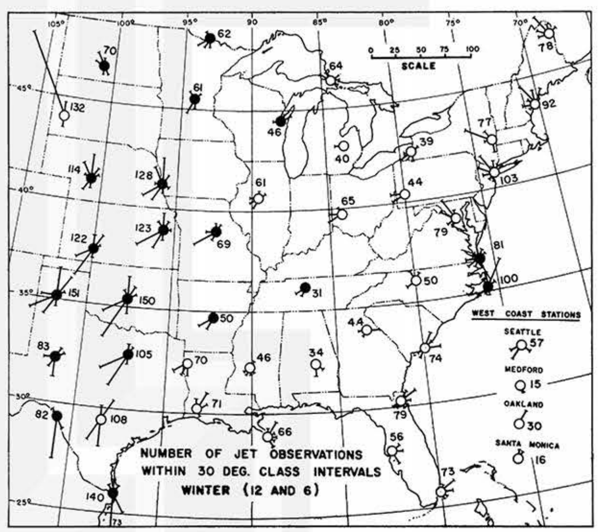

Fig. 5. Frequency distributions of Criterion 1 low-level jet observations within 30-degree class intervals of wind direction at the level of maximum wind. Distributions are for winter months (October through March). Total numbers of jets observed during the twelve winter months examined are shown as well. A black circle indicates more jets observed in summer than in winter.

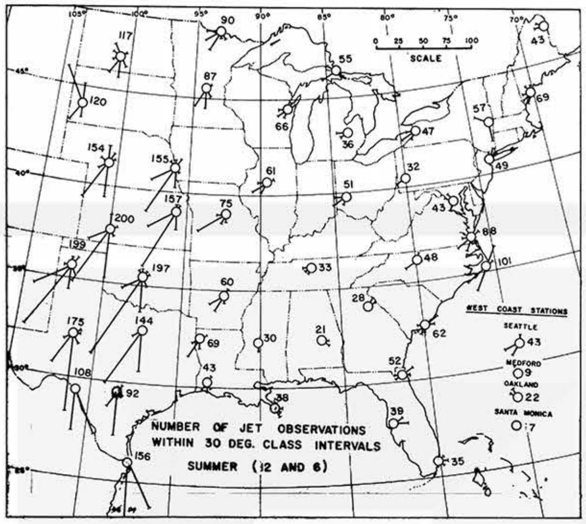

Fig. 6. Same as Fig. 5 except for summer (April through September).

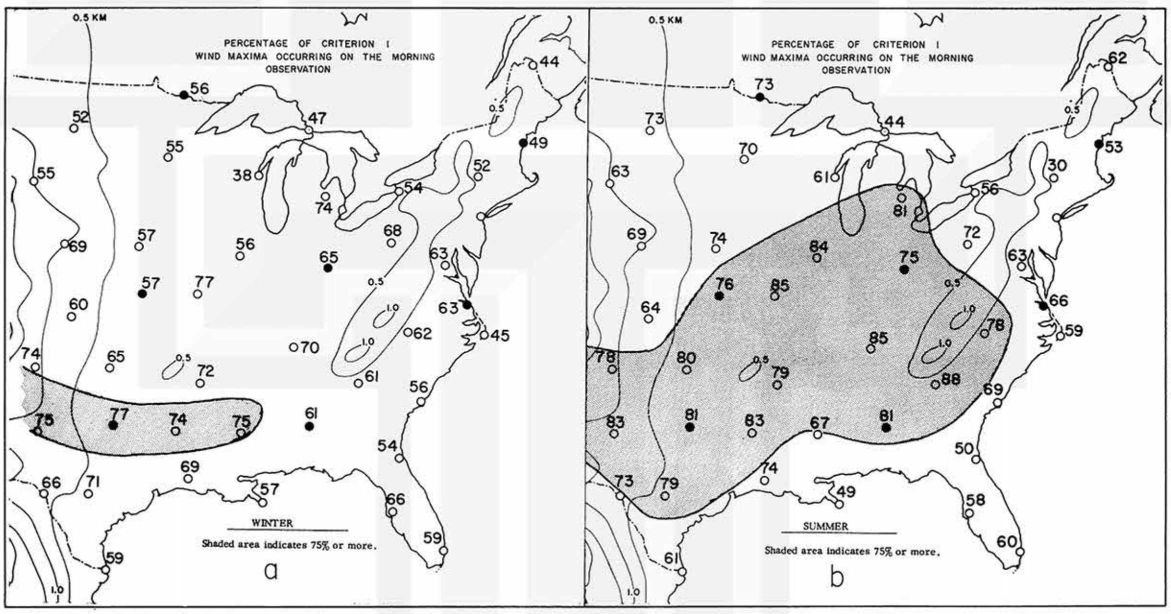

Fig 7. Percentage of Criterion I jets occurring on the 06 CST observations. Summer and winter shown separately. Numbers give an indication of the relative importance of the diurnal oscillation of the wind in formation of a low-level jet.

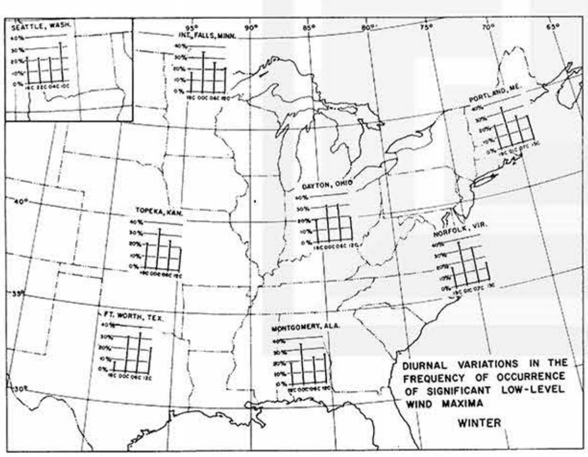

Fig. 8. Percentage of Criterion 1 jets occurring at each observation time using wind data from October 1959 through March 1960.

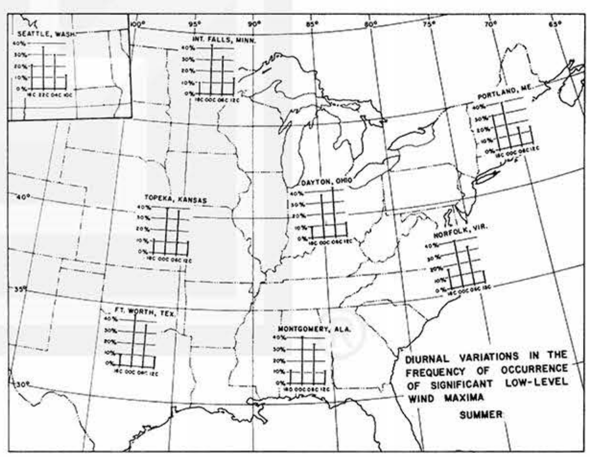

Fig. 9. Same as Fig. 8 except summer months (April 1960 through September 1960).

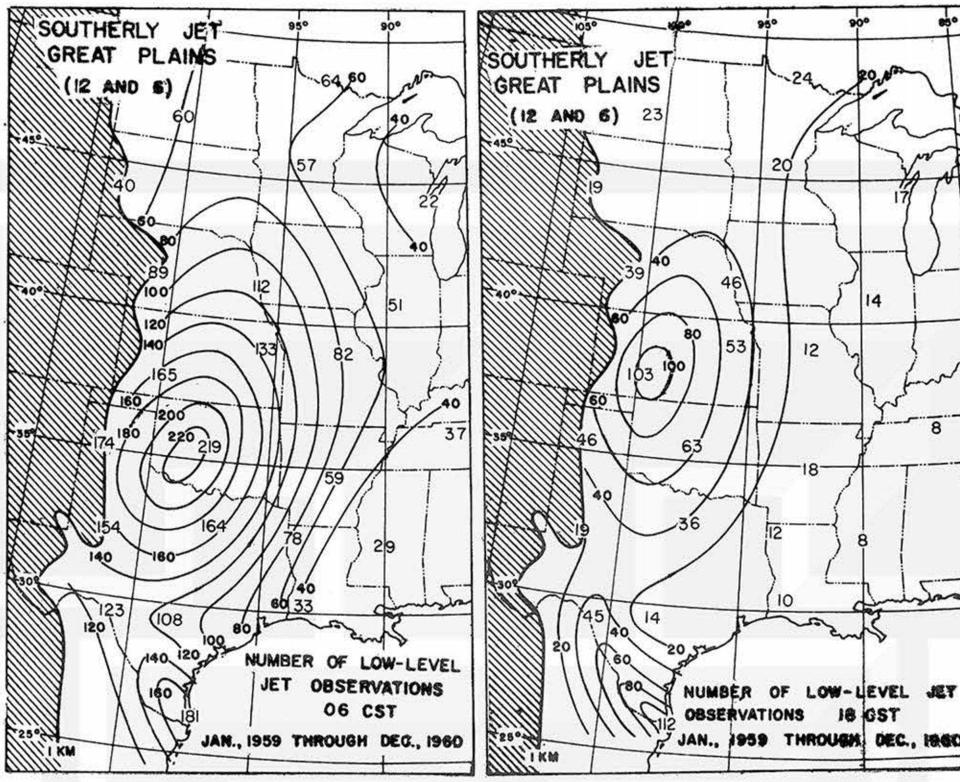

Fig. 10. Numbers of Criterion 1 "southerly-jet" observations at 06 CST and 18 CST separately. Two years of data.

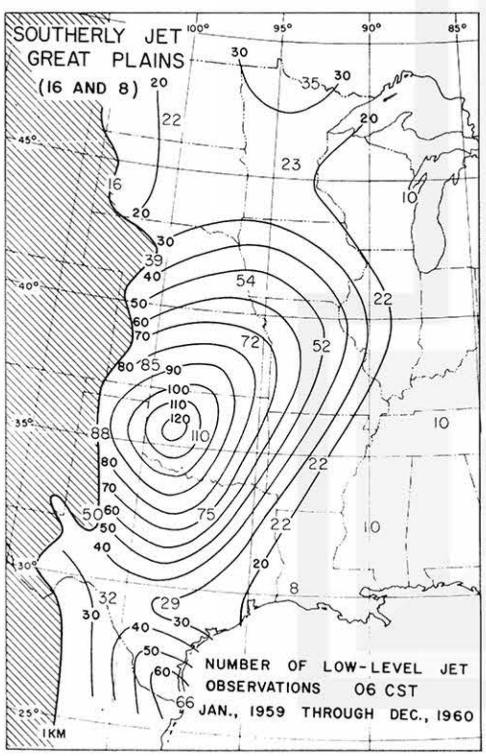

Fig. 11. Numbers of Criterion 2 "southerly-jet" observations at 06 CST. Two years of data.

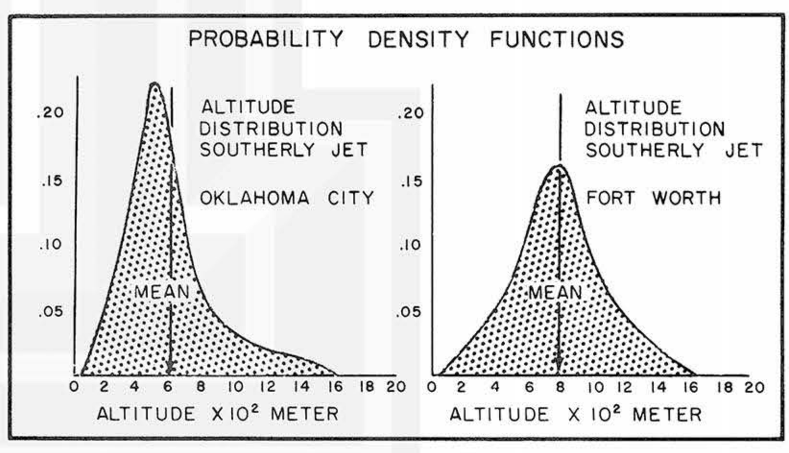

Fig. 12. Estimated altitude distributions of Criterion 1 early morning "southerly-jet" observations at Oklahoma City and Fort Worth. Curves have been normalized. That is, the probability of observing a jet between two levels is given directly by the area under the curve within the interval so defined. Distributions at other stations in the region of the "southerlyljet" are similar.

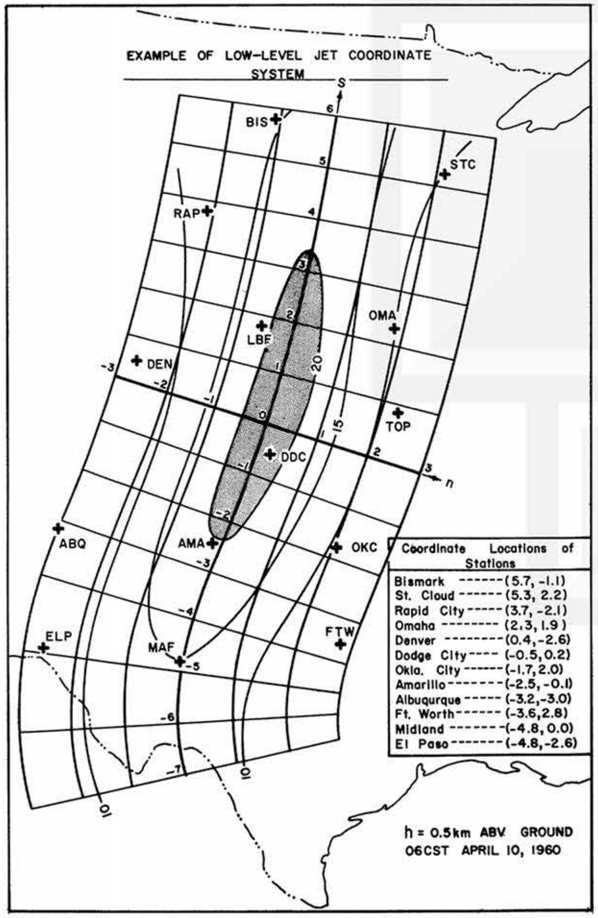

Fig. 13. An example of the low-level jet coordinate system used in the study of the large-scale "southerly jet." Rawinsonde stations in the vicinity of the jet are indicated by crosses and identified by their standard three-letter designators. Coordinate locations of each station at this particular time are given in the lower right. Isopleths are labelled in m sec^{-1} and shaded area denotes jet core where wind speeds are greater than 20 m sec^{-1}.

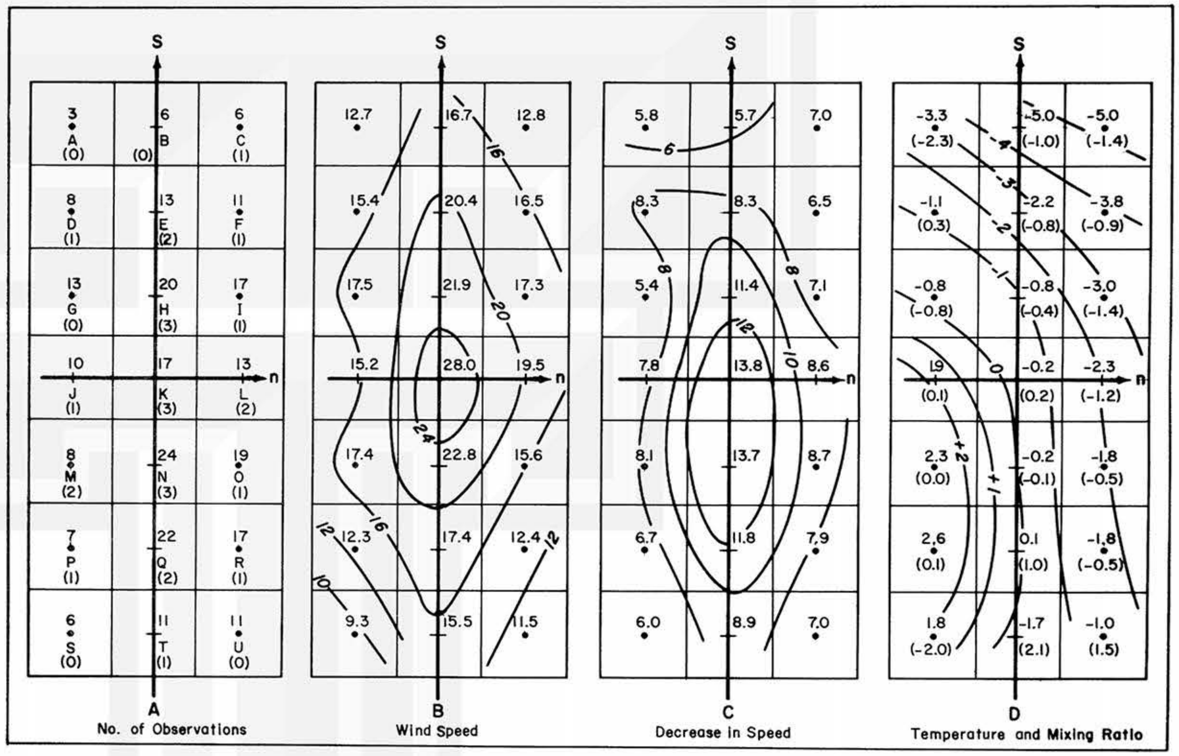

Fig. 14. Twenty-eight case averages in low-level jet coordinate system. Temperatures and mixing ratios refer to the 850 mb level and are departures in deg C or in gm kgm^{-1} from the 850 mb temperature or mixing ratio at the core of the jet. Wind speeds and decreases are in m sec^{-1} and speeds refer to the level of maximum wind.

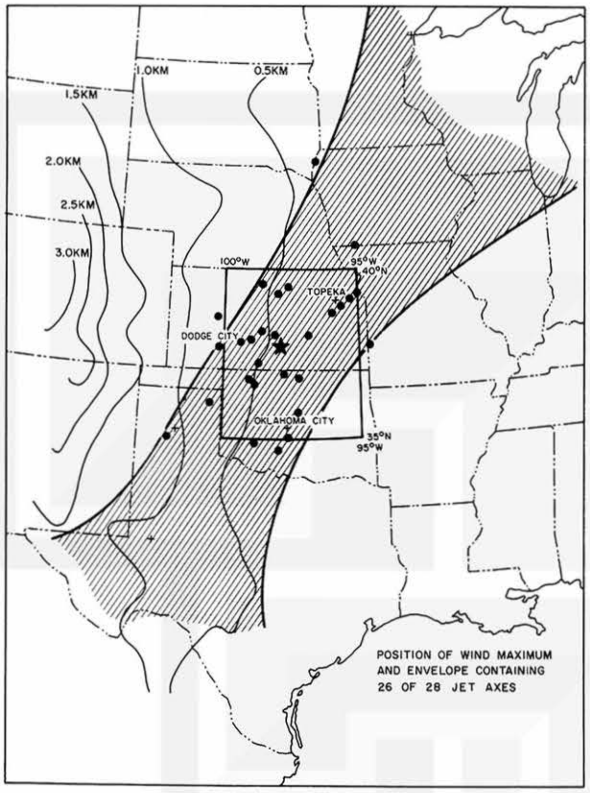

Fig. 15. Location of jet core (center of jet co-ordinate system) in each of the 28 cases. A star indicates the median latitude and longitude of the centers. The shaded area includes the low-level jet axis in 26 of the 28 cases.

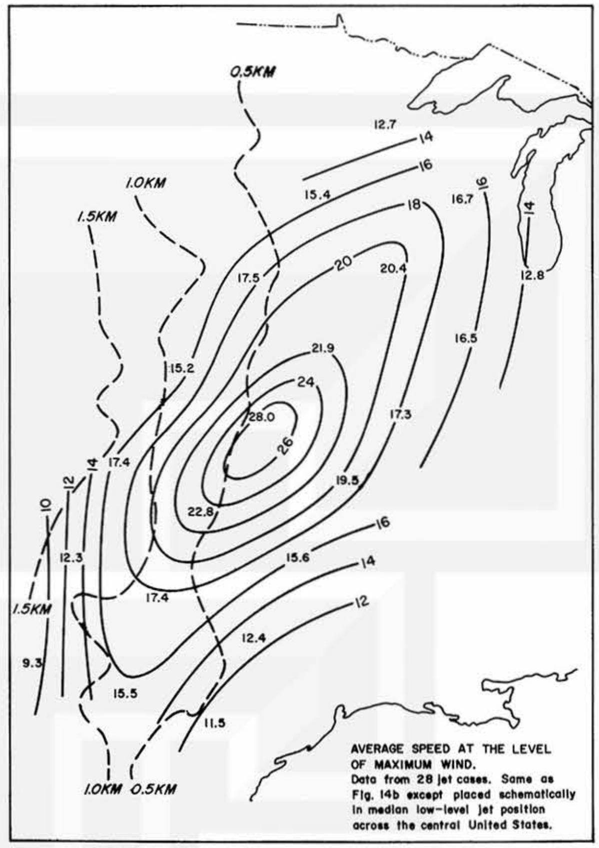

Fig. 16. Shows the mean isotach pattern at the level of maximum wind (in m sec^{-1}), the typical scale and orientation of the jet in the 28 cases examined.

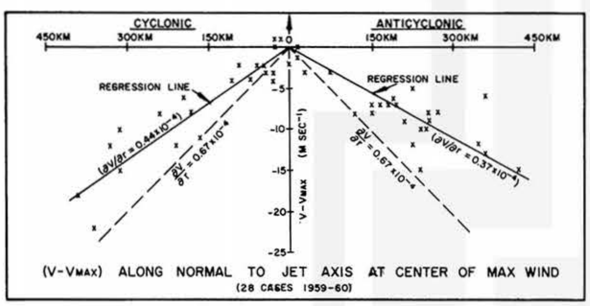

Fig. 17. Decrease in wind speed normal to the jet. The x's indicate the difference between observed wind at stations within approximately 150 km from the normal to the jet through coordinate center (Fig. 13) and the analyzed maximum wind at the jet core. Regression lines through the origin estimate mean wind shear on cyclonic and anticyclonic flanks. Dashed lines give extreme values of shear.

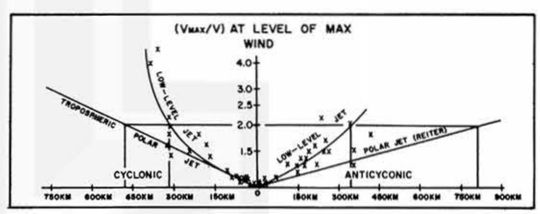

Fig. 18. Ratio between observed and core velocity vs distance from the core of the jet. Same data as in Fig. 17. Note half-power points for low-level jet and for polar jet as given by Reiter (1963).

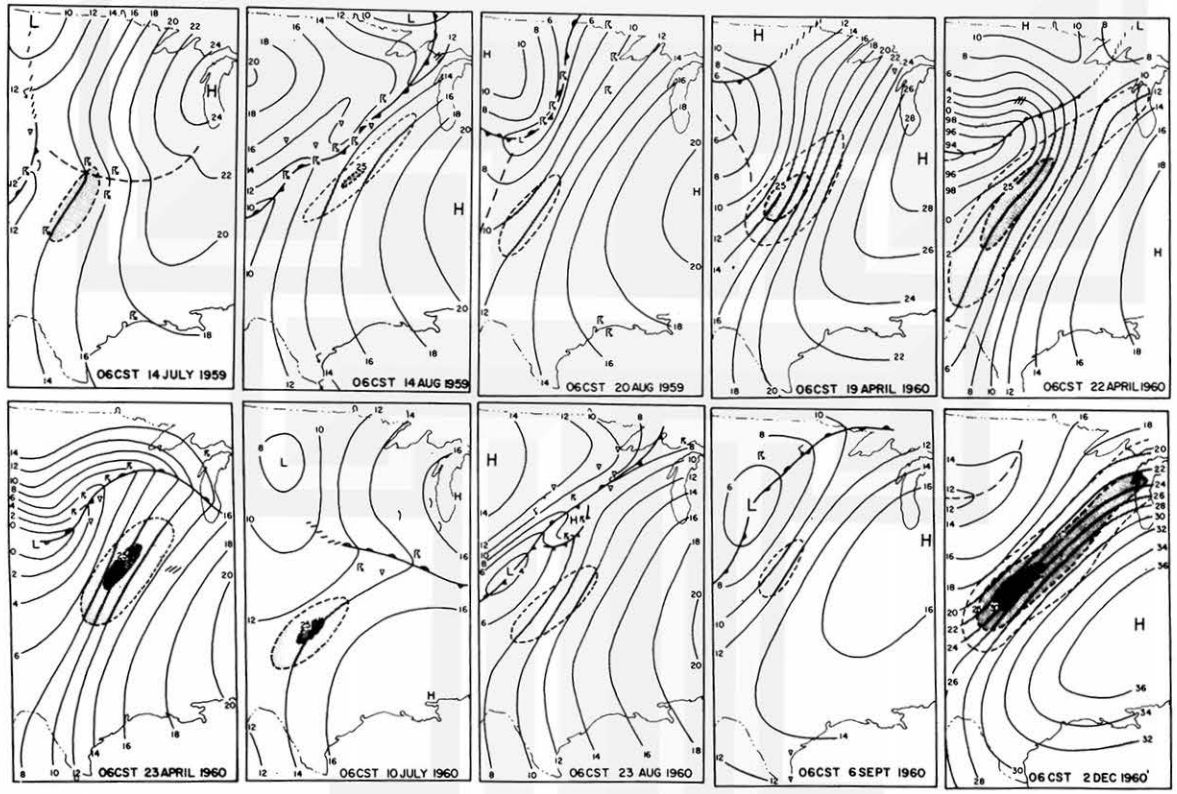

Fig. 19. Sea-level isobars in each of the 10 early-morning, "southerly-jet" cases used in comparison of geostrophic and observed winds. Standard weather symbols are used. Shading indicates region where wind speeds exceed 20 m sec^{-1} at 500 m above the ground. Isotachs for 25 and 30 m sec^{-1} are shown as well.

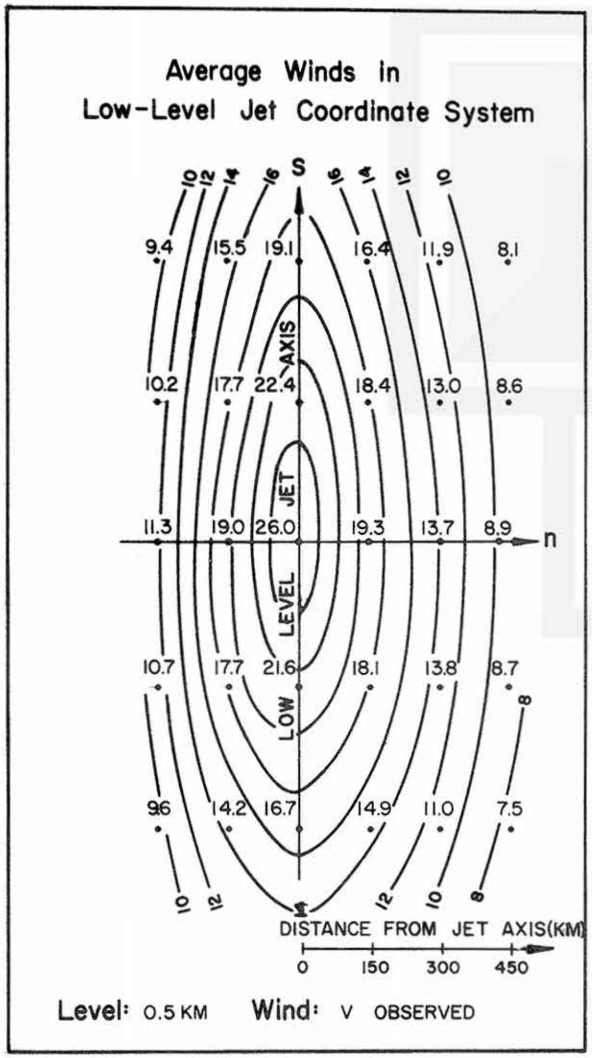

Fig. 20. Mean V component (component along the jet) at 500 m above the ground for 10 early-morning, "southerly jets." Jet coordinate system as in Fig. 13. Cases described in Fig. 19.

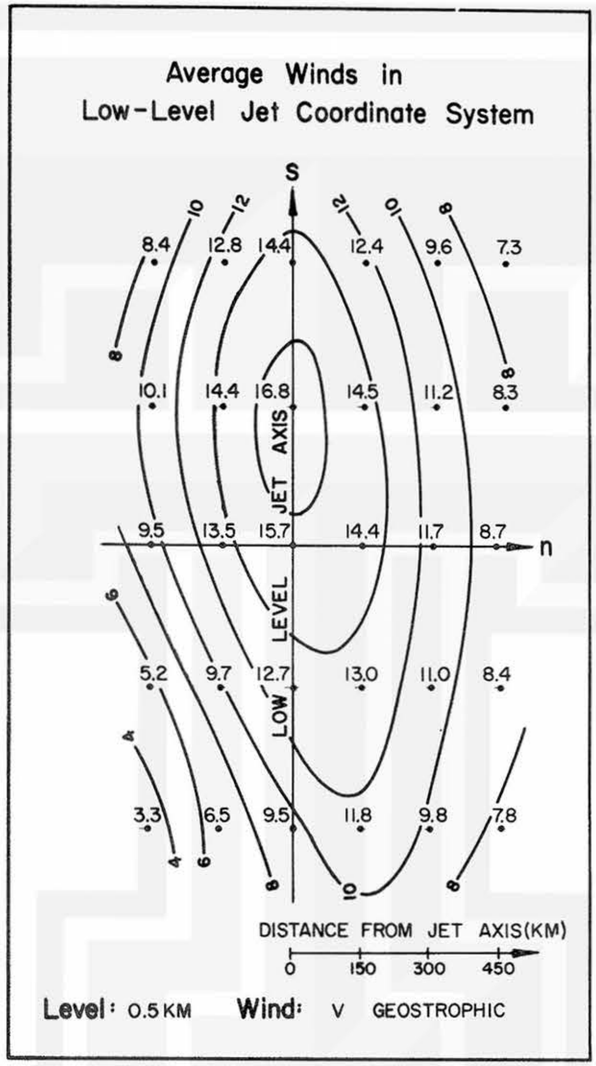

Fig. 21. Same as Fig. 20 except average V component of the geostrophic wind.

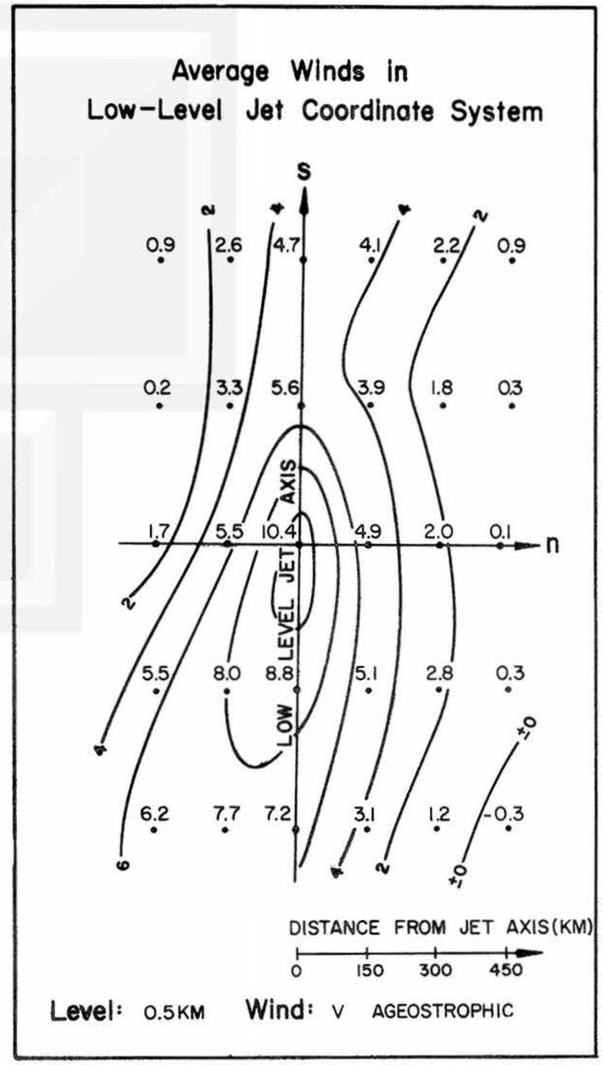

Fig. 22. Same as Fig. 20 except average V component of the ageostrophic wind.

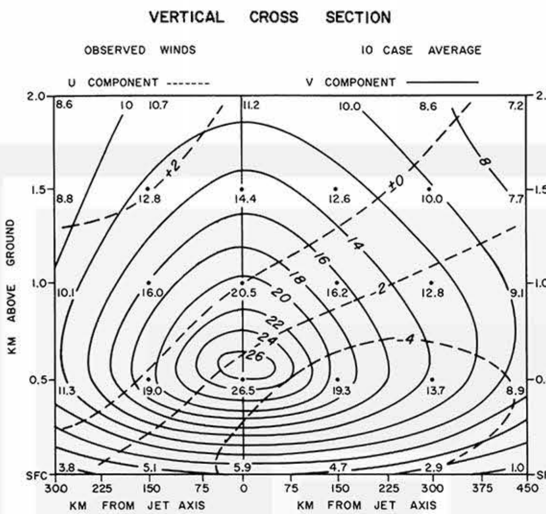

Fig. 23. Mean cross section through the core of the jet, normal to the jet, from the surface to 2 km above the ground. V component (component along the jet) given by solid lines, U component (normal to the jet) by dashed lines. Plotted numbers are machine averaged V components in jet coordinate system determined from isotach analyses at intervals of 500 m above the ground. Averages are for 10 early-morning "southerly jets) as shown in Fig. 19.

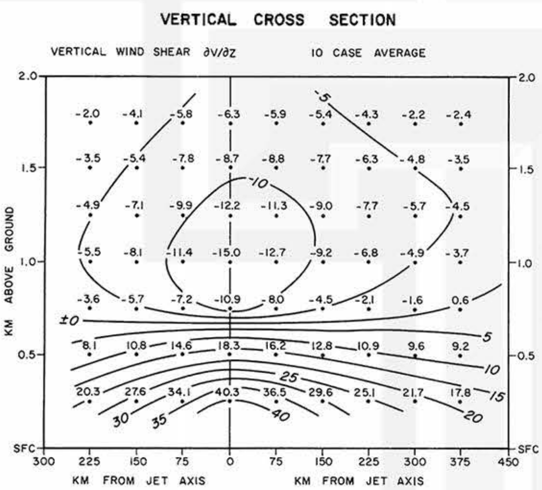

Fig. 24. Mean cross section through the core of the jet. Average vertical wind shear $\partial V/\partial Z$ in m sec^{-1} km^{-1} for 10 cases in Fig. 19.

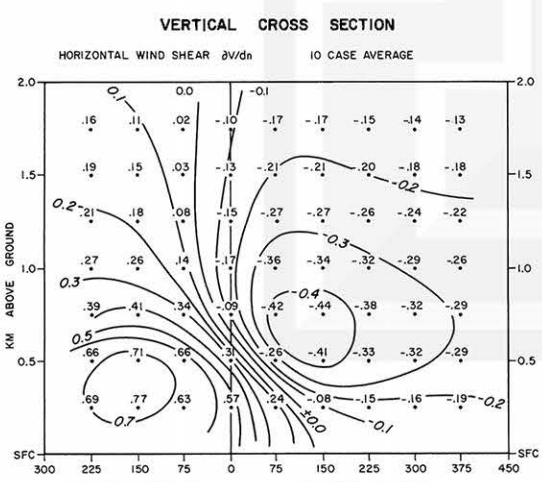

Fig. 25. Mean cross section through the core of the jet. Average horizontal wind shear $\partial V/\partial n$ in units of 10^{-4} sec^{-1}. Horizontal wind shear is 0 at the core of the jet but the - line does not lie along the axis of maximum wind in Fig. 23 because of the terrain slope (see equation 3).

APPENDIX

A considerable amount of data was gathered in the original study of Criterion 0 wind maxima which relates to the diurnal oscillation of the boundary layer winds and to diurnal oscillations in the speed and altitude of boundary layer wind maxima. The existence of the diurnal wind oscillation has been demonstrated by Wagner, Blackadar, Hering and Borden (1962) and others. The data presented here, however, refer specifically to the winds at the level of maximum wind and cover a much larger data sample than has previously been examined.

Results presented are based upon the hand analysis of the 8 rawinsonde stations listed in Table 1 of the text. Four times daily observations were examined for a one-year period. A significant wind maximum was considered to be any wind maximum occurring within the first 1500 m above the ground where the wind speed decreased by at least 3 m sec^{-1} to the next higher minimum or to the 3 km level, whichever was lower.

Frequency of occurrence. The number of jet observations at each station at each observation time is listed in Table A1. The greatest number of jets were recorded on the observation closest to midnight at each station. Second highest frequencies are found on the morning observation. At Fort Worth, Texas, midnight wind maxima were found on 65 percent of the days for the entire year.

TABLE A1

NUMBER OF JET OBSERVATIONS BY OBSERVATION TIME AND STATION. SAMPLE A.

	Montgomery	Ft. Worth	Norfolk	Dayton	Topeka	Portland	Int. Falls	Seattle
00	92	135	143	101	133	141	119	122
06	175	235	221	182	210	163	175	167
12	144	222	194	137	198	138	152	166
18	88	146	114	84	152	110	123	158
Total	499	738	672	504	693	552	569	613

Altitude. Mean altitudes at each of the observation times are summarized in Table A2.

Daytime jet observations are consistently and significantly higher than those during the night. Altitudes of the nighttime maxima are in good agreement with previous estimates (Hering and Borden, 1962, and Blackadar and Buajitta, 1957) on the altitude of maximum amplitude in the nocturnal increase in winds.

An increase in altitude during the night, predicted by Blackadar, does show up weakly in the mean altitudes at seven of the eight stations in Table A2, however, in a fairly high percentage of the cases, wind maxima were actually observed to descend during the same period (see also Novozhilov, 1961). For example, at Fort Worth, Texas, of a total of 131 days on which successive jet observations were reported at both 00 CST and 06 CST, the height of the jet increased during the six-hour period in 76 cases and decreased in 35. Cases were not included in which there were obvious changes in air mass between successive observation times.

TABLE A2

MEAN ALTITUDES, ENTIRE YEAR, SAMPLE A.
HTS. ARE IN KMS ABOVE THE GROUND

	00 GCT	06 GCT	12 GCT	18 GCT
Fort Worth	.84	.64	.70	.92
Topeka	.84	.72	.78	1.00
Int. Falls	.84	.66	.69	.91
Montgomery	.79	.65	.69	.91
Norfolk	.75	.70	.63	.73
Seattle	.70	.58	.66	.76
Dayton	.76	.73	.78	1.02
Portland	.72	.70	.71	.87

TABLE A3

MEAN SPEEDS, ENTIRE YEAR, M SEC^{-1}

	00 GCT	06 GCT	12 GCT	18 GCT
Fort Worth	10.9	13.0	12.9	11.6
Montgomery	10.7	10.4	10.4	10.9
Topeka	13.4	14.2	14.0	13.5
Dayton	12.9	12.6	13.5	14.6
Portland	13.0	13.4	12.6	13.8
Int. Falls	11.5	12.6	13.1	12.8
Seattle	11.2	10.4	10.4	10.4

While little that is definitive can be said about the changes in altitude between 06 GCT and 12 GCT, the tendency for the wind maxima to lower during the evening and to lift again before noon is clear.

Speed at the level of maximum wind. Mean speeds of the low-level wind maxima at each of the observation times are shown in Table A3. It had been expected that, if Blackadar's hypothesis were essentially correct about the dynamics of a reasonable percentage of the nighttime wind maxima, mean wind speeds on the nighttime observations would be significantly greater than those during the day. Presumably, the effects of causes other than the diurnal oscillations of the wind would cancel out at the various observation times. The type of variation expected is apparent at Fort Worth and Topeka. At other stations, however, the strongest wind speeds occur with about equal regularity on daytime and nighttime observations. Statistical tests for the significance of the differences between the means are not justified because wind speeds on successive jet observations are not independent of each other.

By considering only "paired" jet observations (cases in which wind maxima were recorded on at least two successive wind observations), it was possible to obtain a sample of relatively independent data which should actually give a better indication of the reality of diurnal oscillations in speed at various locations.

Speed differences between paired observations. Six-hour speed changes between successive or paired jet observations were tabulated separately for winter and summer months (October through March and April through September respectively). All cases where an obvious frontal passage occurred during the six-hour period or where wind maxima were recorded at several levels on the same observation were ignored. In Table A4, paired observations have been classified as representing simply an increase or a decrease with time in the wind speed. The data has been presented for the summer months alone. An asterisk indicates that the indicated tendency is statistically significant at a .01 level of probability.[7]

TABLE A4

SPEED CHANGES AT THE LEVEL OF MAXIMUM WIND. PAIRED OBSERVATIONS

Station	V18C-00C		00C-06C		06C-12C	
	Inc.	Dec.	Inc.	Dec.	Inc.	Dec.
Fort Worth	57	7*	29	59*	7	41*
Topeka	39	6*	35	37	15	35*
Int. Falls	27	5*	32	22	8	18
Dayton	24	11	24	18	5	15
Montgomery	20	7*	19	26	5	15
Norfolk	38	13*	35	34	12	27
Portland	23	11	12	25	10	11
Seattle	17	10	15	25	4	9

[7] The data were first tested for independence by computing the number of runs of elements of two different types (see, for example, Brownlee, 1960) P values were then computed by computing the probability of obtaining the observed distributions of increases and decreases in independent drawings from a population of paired jet observations in which increases or decreases are equally likely.

At each of the stations in Table A4, there appears to be a strong tendency for wind speeds in the jet to increase during the evening hours. This tendency is statistically significant at only five of the stations; however, it is still quite pronounced at the remaining stations, Dayton, Portland, and Seattle. Variations are in exactly the opposite sense during the morning hours (06 CST to 12 CST). Significance levels here were generally lower, however, since in most cases fewer paired jet observations were found than during the evening.

It is much more difficult to define a trend during the period from midnight to 06 CST. At Fort Worth, Texas, however, there appears to be a clear tendency for maximum speeds to occur on the 00 CST observation, indicating perhaps that the actual time of the maximum wind speed is generally reached between midnight and 03 CST. At Topeka, Kansas, the distribution of increases and decreases is about even and at International Falls, Minnesota, there is a slight tendency towards increasing wind speeds, indicating, in this case, a shift in the average time of the wind maxima to somewhere between 03 CST and 06 CST. The same shift with increasing latitude towards later times is indicated by a comparison of the nighttime paired observations at Montgomery, Alabama and at Dayton, Ohio, and again, along the east coast between Norfolk and Portland.

This trend is exactly opposite to that which would be expected to arise from latitudinal variations in the period of the inertial oscillation (see section 3.7).

Results from a comparison of paired observations in winter were similar to those in Table A4. In general, the diurnal oscillations in speed were somewhat less pronounced; however, an increase in speeds during the evening hours was still reported in the majority of the paired observations at all stations and the percentage of increases at both Topeka and Fort Worth was significant at a .01 level of probability.

The failure of these oscillations to appear in the mean data from stations other than Fort Worth and Topeka (Table A3) must be attributed in part to the sensitivity of the mean to a small number of extreme observations occurring by chance at one or more of the observation times and, since a comparison of median speeds was only slightly better than the comparison of means in picking out this oscillation, to the presence of a large number of isolated strong daytime jet observations. Since the shear or wind decrease criterion imposed at this point of the study was only 3 m sec^{-1} a number of cases occurred in which wind maxima were reported with wind speeds in excess of 20 m sec^{-1}. In this case, the requirement of 3 m sec^{-1} is probably not sufficiently strong to rule out either observational error or short period turbulent fluctuations, which should be expected to occur most often during the daytime when vertical accelerations of the air are at a maximum.

The results from Table A3, therefore, do not indicate the absence of a regular diurnal oscillation in speed in regions outside the south-central United States. Such an oscillation is clearly demonstrated in Table A4.

Further examination of diurnal oscillations in wind speed at Fort Worth, Texas. Figure A1 is a plot of the vector mean winds on sixteen summer days during which low-level jet profiles were reported on four successive observation times. Anticyclonic rotation of the mean wind vectors around the overall mean is clearly apparent, and the figure is very close to the schematic model proposed by Blackadar.

Similar diagrams have been constructed by Blackadar (1957) and Hering and Borden (1962) from wind data at constant levels above the ground in this area during selected periods of relatively stable flow. The mean amplitude of the $\mathbb{V}'$ vector in Fig. A1 is approximately 3 m sec^{-1}, the magnitude of the oscillation determined at Fort Worth, by Hering and Borden from wind data during July, 1958.

Mean wind speed profiles from the surface to 10 km are shown in Fig. A2 for the same selected "jet days." A diurnal oscillation in both speed and altitude is clearly apparent. All four curves intersect at approximately 100 m above the ground and again at 2 km, in close agreement with previous data (Blackadar and Buajitta, 1957, and Hering and Borden, 1962) on the vertical extent of the nighttime shift towards higher wind speeds in this area.

In Fig. A2, wind speeds at jet level are essentially the same at 12 CST and 18 CST and again at 00 CST and 06 CST. These observation times were combined to give frequency distributions of wind speed for the entire year on "daytime" and "nighttime" jet observations (Fig. A3). The diurnal oscillation in speed is apparent as a simple linear translation of the distribution towards higher speeds at night.

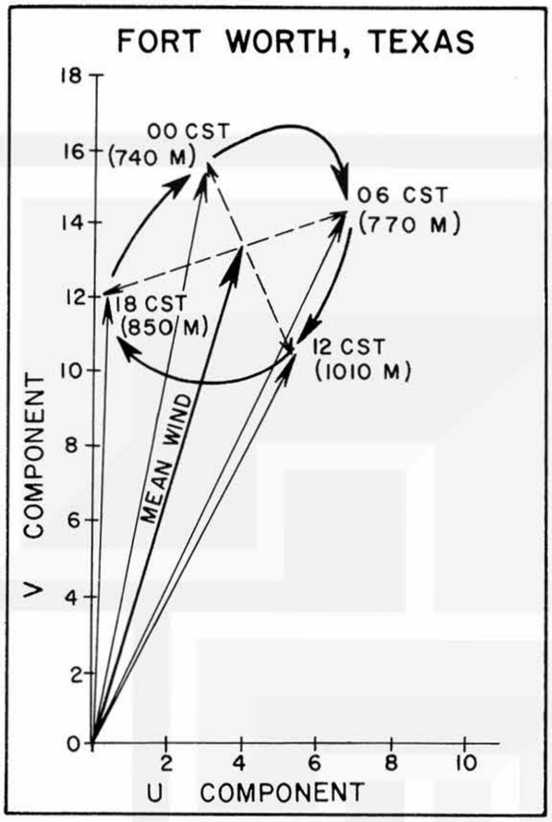

Fig. A1. Vector mean winds on sixteen summer days with Criterion 0 wind maxima on all four daily observations. Mean altitudes in m above the ground at each observation time are indicated in parentheses. Note the rotation about the mean wind.

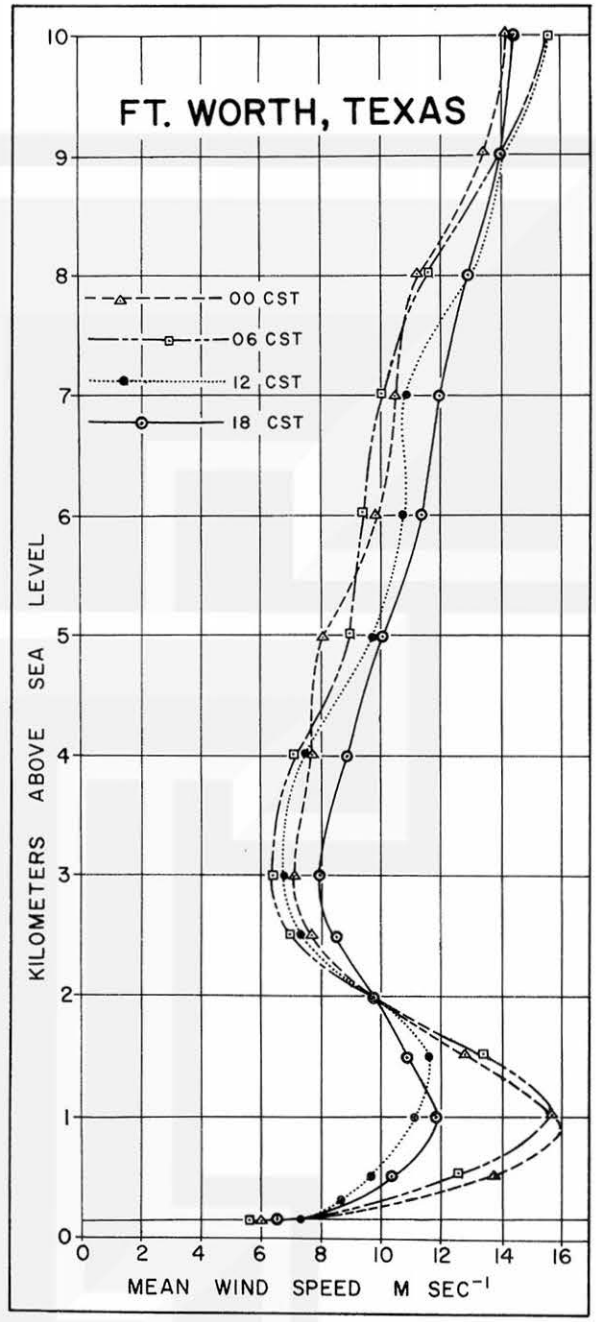

Fig. A2. Mean wind speed profiles for same sixteen summer days as in Fig. A1. Note the strong jet profiles at 00 and 06 CST and the cross-over point at 2.0 km.

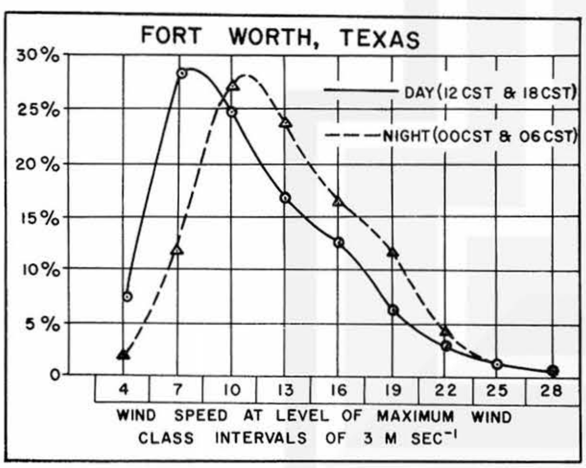

Fig. A3. Percentage of total Criterion 0 jet observations falling within 3 m sec^{-1} class intervals of speed at the level of maximum m wind. 457 nighttime observations and 281 during the day. Note the higher speeds on nighttime observations.

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