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CLIMATOLOGY OF THE LOW LEVEL JET

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ABSTRACT

Geographical and diurnal variations in the frequency of occurrence of strong low level wind maxima are determined using 2 yr. of wind data from 47 rawinsonde stations in the United States. Maximum frequency of occurrence is found in the Great Plains at approximately 37°N. and 98°W. The vast majority of jets in this region occur with southerly flow. Southerly wind maxima appear on both morning and afternoon soundings but occur with much greater frequency, over a larger area, on the morning observations.

Twenty-eight morning jet cases are used to determine average synoptic-scale wind and temperature patterns in the vicinity of the jet. Diurnal wind oscillations are examined by comparisons of jet frequencies, speeds, and altitudes on four-times-daily observations. The oscillation is similar to that described by Blackadar; however, there is no apparent tendency for the latitudinal variation in period of the oscillation which Blackadar's model implies.

1. INTRODUCTION

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 2 yr. 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 specifically with the southerly low level jet in the Great Plains. Previous descriptions of the low level jet in this area have generally involved special observational programs, describing the time variations in the wind at a particular point in space,[1] or, for a limited period of time, along a single line of stations.[2] This study examines the synoptic-scale structure of the low level jet through the standard network of radiosonde and rawinsonde stations.

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 are a significant hazard to jet aircraft on approach. The presence of a strong jet profile near the ground can greatly increase the rate of spreading of forest fires (see Barad [2]). Of greater meteorological interest, the southerly low level jet across the south-central United States is apparently related to the development of thunderstorms over the Great Plains. Diurnal oscillations in the speed of this jet are considered to be responsible for the nighttime maximum in thunderstorm activity observed across a large portion of the Midwest (see, for example, Curtis and Panofsky [9]).

2. EXPLANATIONS OF THE JET

Before describing the 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.

Wagner [39] explained the diurnal oscillation of the wind in this region as a result of diurnal oscillations in the pressure and temperature fields. He proposed that these oscillations arise as a combined effect of the following circulations:

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

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[1] See studies by Izumi [20] and Gerhardt [12, 13] based on wind observations from the 1,400-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 [35] and Hoecker [17, 18].

b. a circulation between the continent and the ocean;

c. a circulation between the mountains and the plain.

According to Lettau [24], low level wind maxima forming at night in the central United States are not accompanied by increasing geostrophic winds and Blackadar [3] 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.

This diurnal oscillation of the wind, taking place over a broad area, is thought to give rise to large-scale southerly jets of the type originally described by Means [25, 26] and Newton [28].

Wexler [40] has denied that the southerly jet in this area can be explained by the small-scale radiative and frictional effects alone. According to Wexler, the jet forms as a result of 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. Along the western boundary of the current, where the terrain slopes upward, the air is retarded by friction. The two effects act together to produce a narrow zone of strong southerly wind at low levels along the eastern slopes of the Rocky Mountains.

Blackadar's argument is supported by calculations of wind oscillations arising from hypothetical time and altitude variations of the coefficient of eddy viscosity (Buajitti and Blackadar [7]). Wexler has drawn a physical analogy between the southerly jet and the Gulf Stream (an analogy suggested by Newton [29]). He has transposed numerical solutions for the Gulf Stream flow (Charney [8] and Morgan [27]) to the case of the southerly jet, demonstrating an appreciable concentration of momentum 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 jet are probably correctly explained by Blackadar. Recent studies indicate, however, that the boundary layer oscillation is more complicated than Blackadar supposed.

Holton [19], reviving an original suggestion by Bleeker and Andre [4], has shown that alternate heating and cooling of the slopes of the Rocky Mountains can produce diurnal oscillations of the wind in a boundary layer with *constant* eddy viscosity. Hoecker [18] and Sangster [34] have shown that geostrophic winds in this region are not constant in time as Blackadar assumes. They vary strongly from day to night in an oscillation nearly 180° out of phase with that of the actual wind.

3. CLIMATOLOGY OF THE JET

THE APPROACH

The explanation of the jet by Blackadar implies that it is strictly a nighttime phenomenon; explanations by Wexler and Holton, 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 in 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.

TABLE 1.—*Stations used in the pilot study*

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

DATA SOURCES

A pilot study was carried out first, using wind data from the eight rawinsonde stations listed in table 1. Each of these stations reports wind observations at 6-hr. intervals beginning at 00 GMT. Observations were examined for the 1-yr. 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 2-yr. 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 GMT and 12 GMT. 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. m.s.l. and every 1000 m. at higher levels. In all, approximately 70,000 cards were examined for low level wind maxima.[3]

Figure 1 shows the location and elevation of all 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 small-scale mountain-valley wind systems.

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.

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[3] Computer time for this portion of the study was paid for by grants by the National Science Foundation to the Computation Center at the University of Chicago.

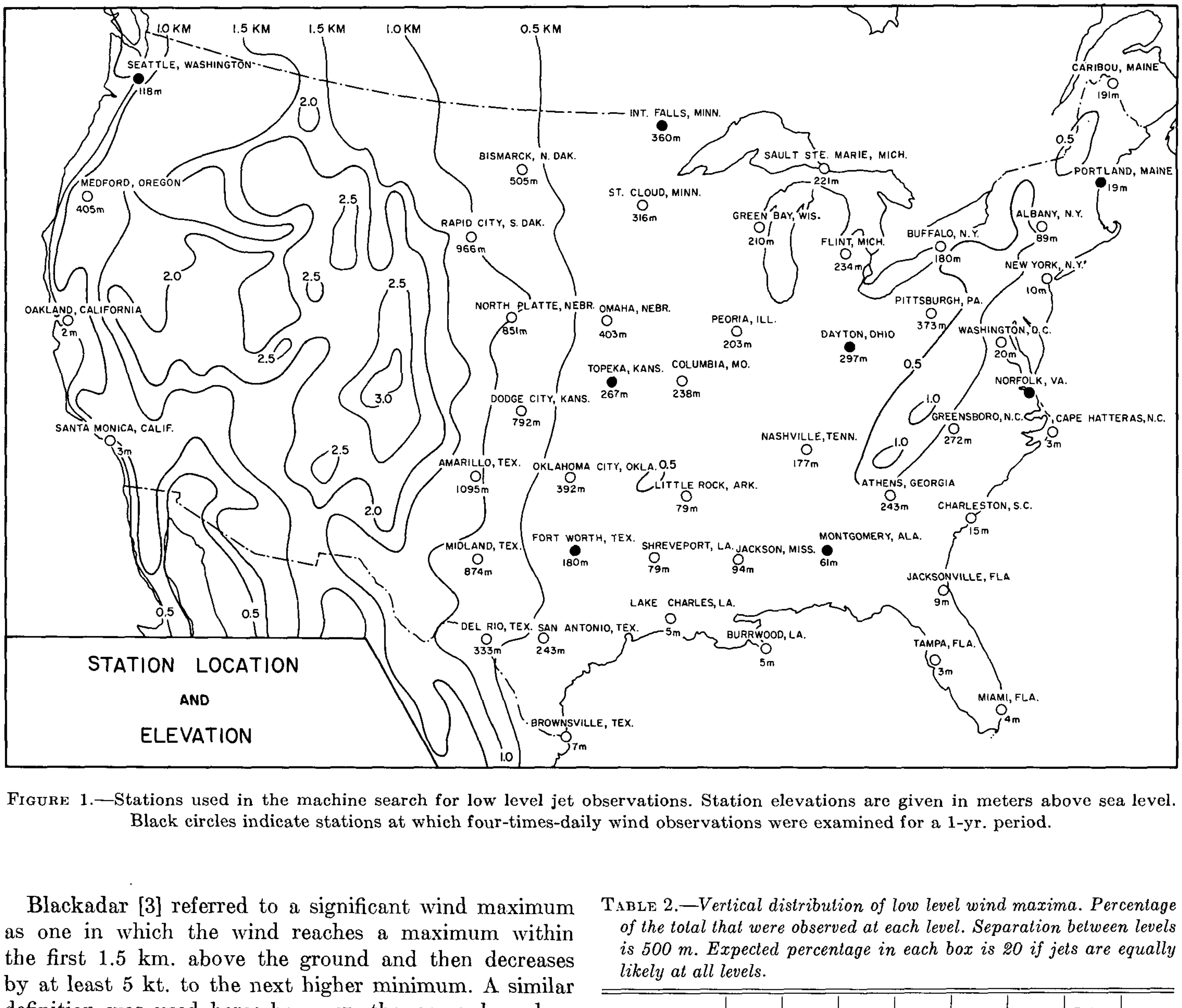

FIGURE 1.—Stations used in the machine search for low level jet observations. Station elevations are given in meters above sea level. Black circles indicate stations at which four-times-daily wind observations were examined for a 1-yr. period.

Blackadar [3] 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 kt. to the next higher minimum. A similar definition was used here; however, the upper boundary was set initially at 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 1-yr. period using wind data from the stations in table 1. If the phenomenon is real, it should be indicated by a zone of high frequency near the ground and then a sharp decrease in jet frequency somewhere within the first 2.5 km. The altitude at which this dropoff occurs 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 eight stations. Cases where jets were recorded at two 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 dropoff in frequency between levels 2 and 3, or, at Forth 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 altitude.

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, Ala.	Fort Worth, Tex.	Norfolk, Va.	Dayton, Ohio	Topeka, Kans.	Portland, Maine	International Falls, Minn.	Seattle, Wash.
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	18.6	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

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 [1] 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 kt.; 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.

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 was 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.

In addition, the eight stations in table 1 were reexamined 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 as Criterion 0.

GEOGRAPHICAL DISTRIBUTION OF LOW LEVEL WIND MAXIMA

Figures 2, 3, and 4 show the number of Criterion 1, 2, and 3 jet observations at each station during the 2-yr. period from January 1959 to December 1960. Frequencies at stations along the west coast are listed in the lower righthand corner of each map. The same percentage of jet observations as observed on complete wind reports was assigned to missing or incomplete observations. Thus, numbers in figures 2, 3, and 4 can be converted to probabilities by dividing by the maximum possible number of observations, 1,462.

The basic pattern in all three figures is the same. Regardless of the particular criterion selected, there is a pronounced maximum in frequency at 95° to 100°W. on the Oklahoma-Kansas border. The zone of maximum frequency is roughly parallel to the Rocky Mountains. Between the Mississippi River and the Appalachian Mountains, the frequency of low level jet observations drops off sharply. In figure 4, for example, 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, Wash., where the frequencies are roughly equivalent to those in the eastern Midwest States.

There is a second but much weaker maximum in frequency along the East Coast. At Criterion 1 (fig. 2), jet frequency at Cape Hatteras is roughly ⅔ of that at Fort Worth; at Criterion 3, however, the ratio between the

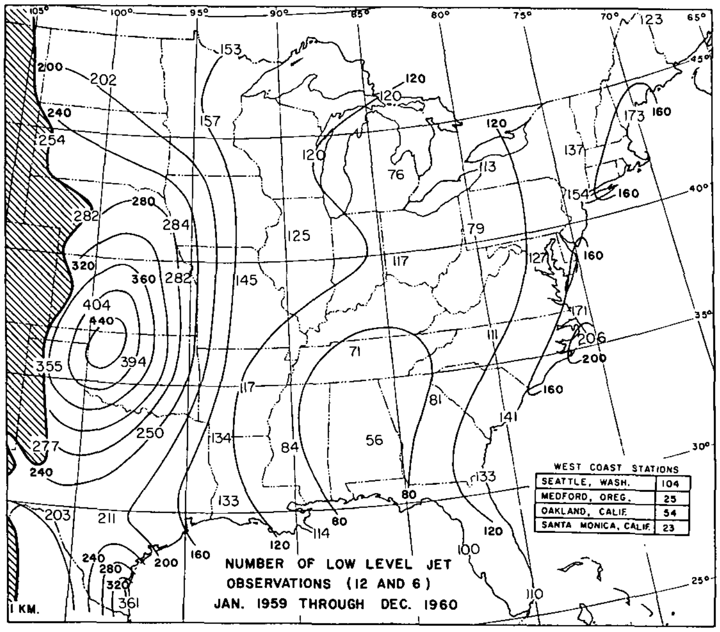

FIGURE 2.—Number of Criterion 1 low level jet observations from January 1959 through December 1960. 18 CST and 06 CST combined.

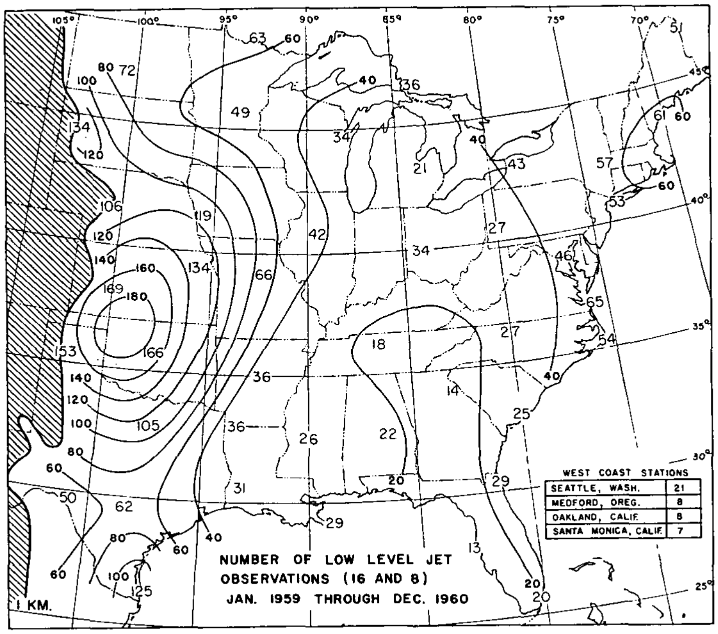

FIGURE 3.—Same as figure 2 except Criterion 2.

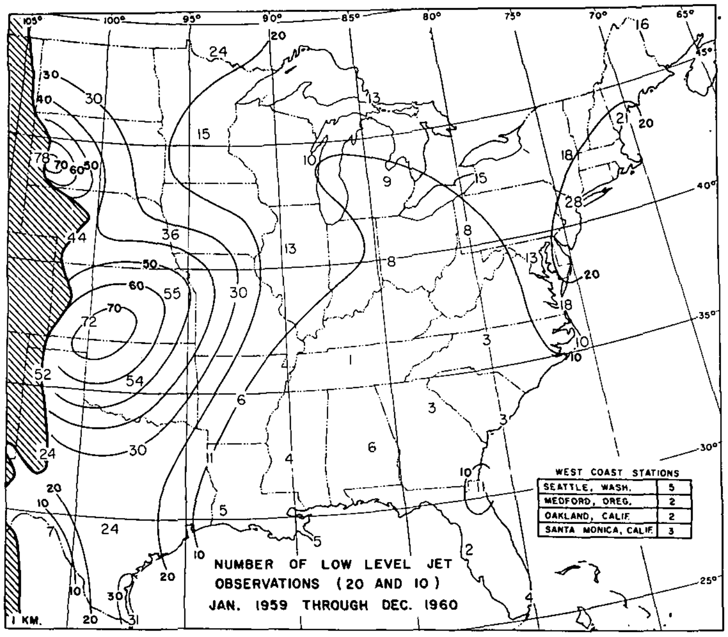

FIGURE 4.—Same as figure 2 except Criterion 3.

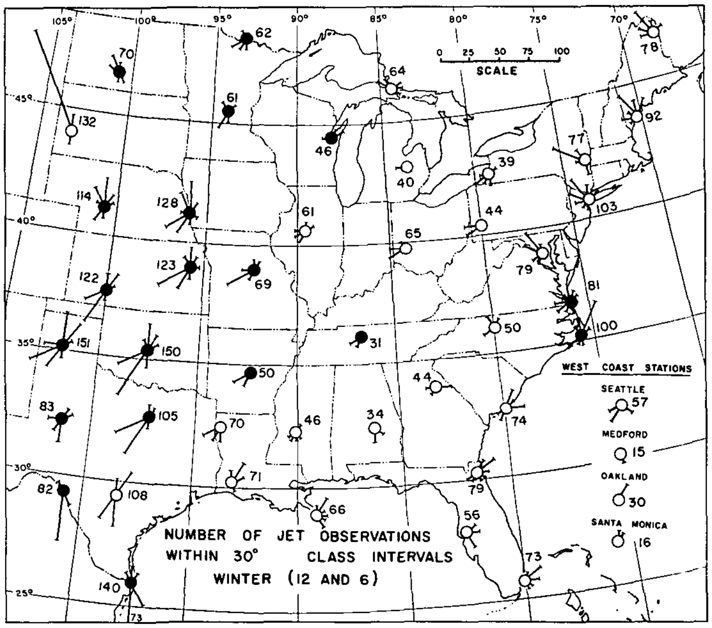

FIGURE 5.—Frequency distributions of Criterion 1 low level jet observations within 30° class intervals of wind direction at the level of maximum wind. Distributions are for winter months (October through March). Total number of jets observed during the 12 winter mo. examined are shown as well. A black circle indicates more jets observed in summer than in winter.

two frequencies drops to ⅓, showing the disappearance of the East Coast wind maxima as criteria for a jet are made increasingly stringent. Criterion 0 frequencies along the East Coast almost match those in the Great Plains (see table 5 in section 6).

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 figures 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).

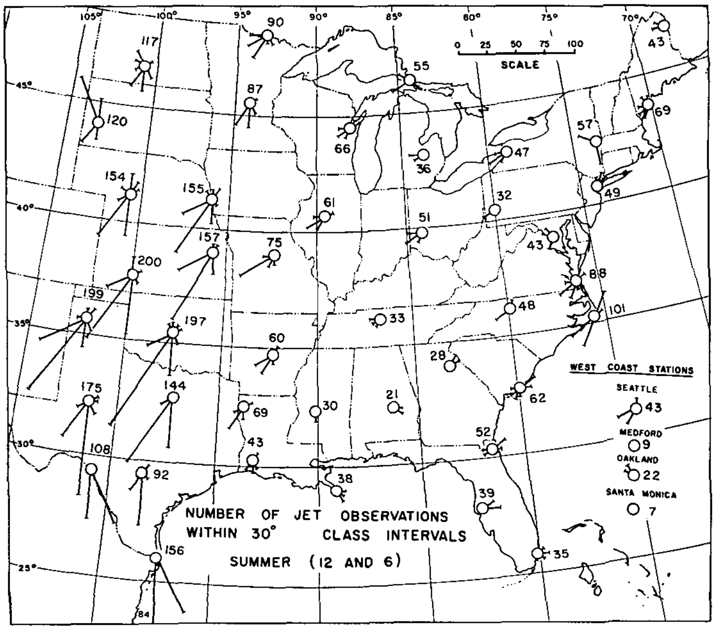

FIGURE 6.—Same as figure 5 except for summer (April through September).

SEASONAL AND DIRECTIONAL BREAKDOWNS

Frequency distributions of Criterion 1 jet occurrence within 30° class intervals of wind direction are shown in figures 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 emphasize 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, wind maxima are more frequent in winter than in summer. In the Great Plains, however, roughly 55 to 60 percent of all jet observations occurred during the 12 summer months examined.

The wintertime directional breakdowns (fig. 5) indicate a bimodality in direction at most of the Great Plains stations. From Kansas southwards, southerly or southwesterly jets predominate. A secondary maximum in frequency from the north extends from North Dakota to Texas. The very large number of northerly jets 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 fronts or shallow, cold Highs in which strong northerly winds near the ground were replaced by weak southerly flow aloft. They 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 [23] 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.

The dominance of southerly wind maxima across the Great Plains is much more pronounced in summer than in winter (compare fig. 5 and 6). Modal wind directions from Brownsville to Omaha shift gradually from south-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 [15]) and of the general large-scale flow decribed by Wexler.

RELATIVE FREQUENCIES AT 00 GMT AND 12 GMT

For the 2-yr. period as a whole, more than half of the Criterion 1 wind maxima were recorded on the morning (12 GMT) observation at 44 of the 47 stations examined. The percentage:

$$r=\frac{\text{jet observations at 12 GMT}}{\text{total jet observations}}\times 100$$

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

Percentages 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 figure 7.)

3) The ratio between evening and morning jet frequencies is greatest at stations away from the coastline. 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. Percentage isopleths 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 maxi-

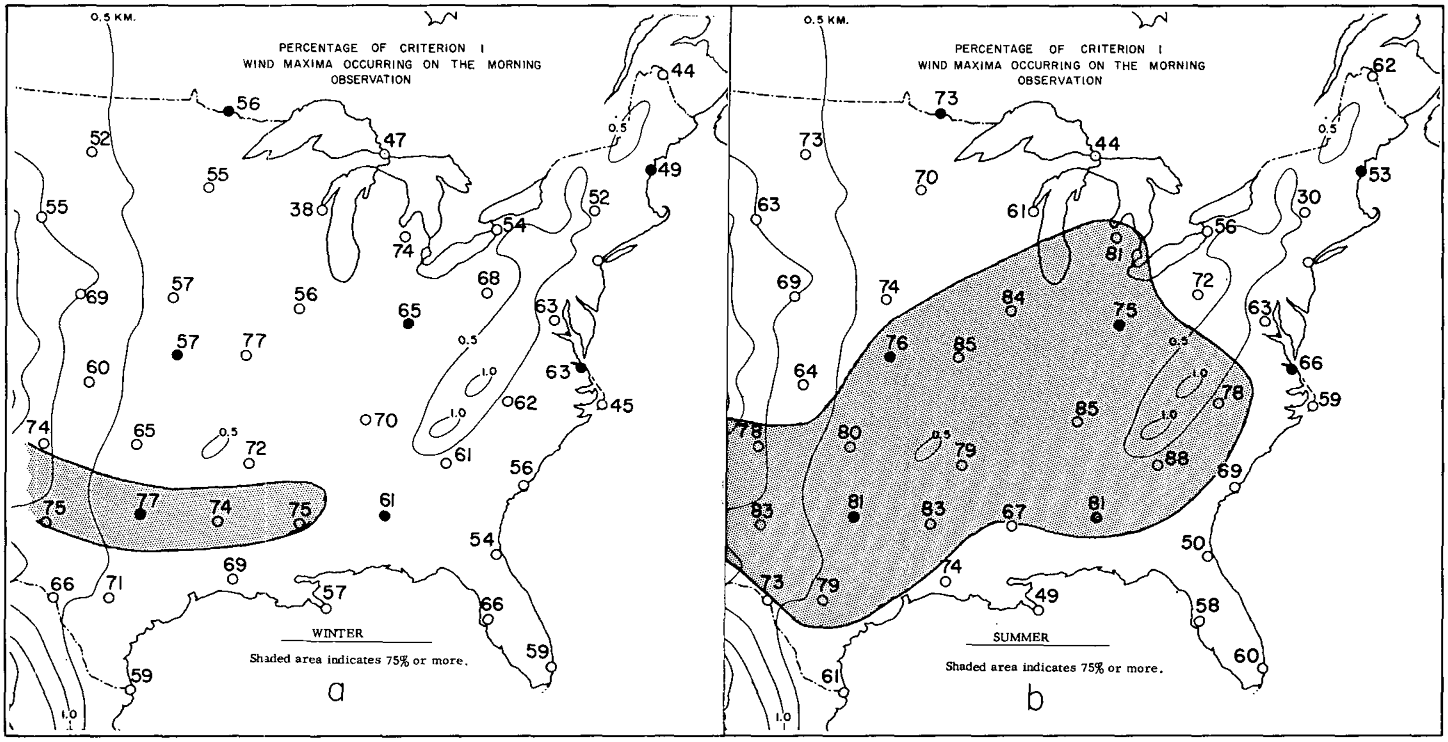

FIGURE 7.—Percentage of Criterion 1 jets occurring on the 06 CST observations in (a) winter, (b) summer. Numbers give an indication of the relative importance of the diurnal oscillation of the wind in formation of a low level jet.

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[4] For example, of 68 Criterion 1 jets observed at Oklahoma City with direction from 330° to 060°, 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, Tex., are even more conclusive: 53 morning northerly jet observations to 17 at 18 CST.

mum frequency in both summer and winter at about 35° lat.

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 consistent with the hypothesis that the amplitude of the diurnal oscillation is greatest near 30°, where the period of an inertial oscillation is 1 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.

Diurnal variations in the frequency of occurrence of Criterion 1 jets are summarized in figures 8 and 9, based upon 1 yr. of four-times-daily observations from stations in table 1. The diurnal variations are more pronounced in summer than in winter. Jet frequency is generally greater at midnight than at 06 CST but the difference is slight, indicating that geographical distributions in figures 2, 3, and 4 should be essentially the same at 00 as at 06 CST.

If Blackadar's hypothesis is correct, the time of maximum jet frequency should shift backwards with increasing latitude. Since the period of an inertial oscillation is

$$P=\frac{2\pi}{f}=\frac{\pi}{\Omega \sin \phi},$$

the rate of rotation of the ageostrophic wind vector depends upon the latitude. The rate at International Falls should be almost 1.5 times that at Fort Worth (periods for a complete rotation are 15.6 and 22.0 hr. 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 3 hr. earlier at International Falls than at Fort Worth. While the time of maximum frequency does shift from 06 CST at Forth Worth to 00 CST at Topeka and International Falls in winter (fig. 8), there is no apparent latitudinal shift during the summer months (fig. 9).

4. CLIMATOLOGY OF THE SOUTHERLY JET

In previous sections it was shown that the frequency of strong low level wind maxima is much higher in a

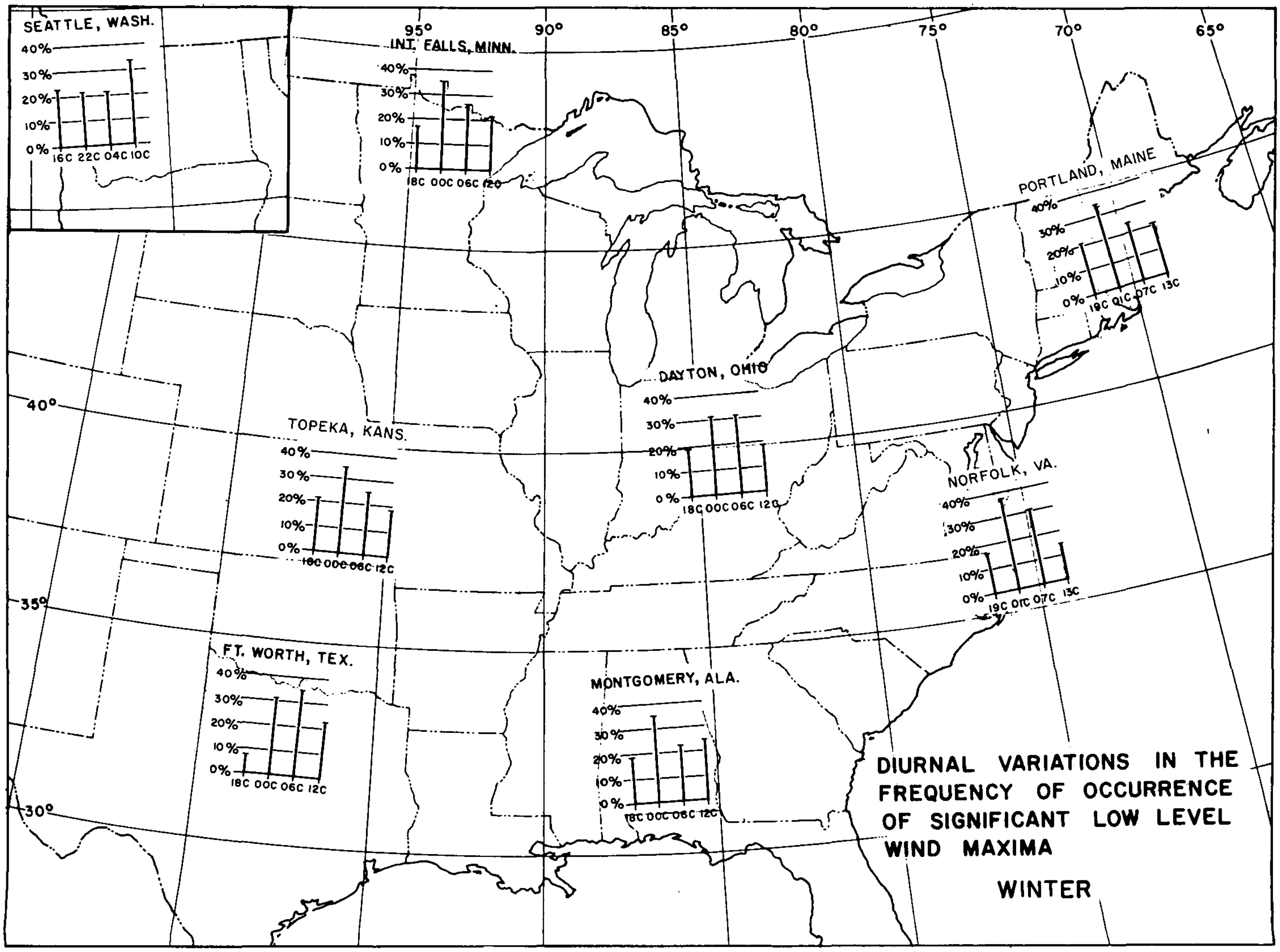

FIGURE 8.—Percentage of Criterion 1 jet occurring at each observation time using wind data from October 1959 through March 1960.

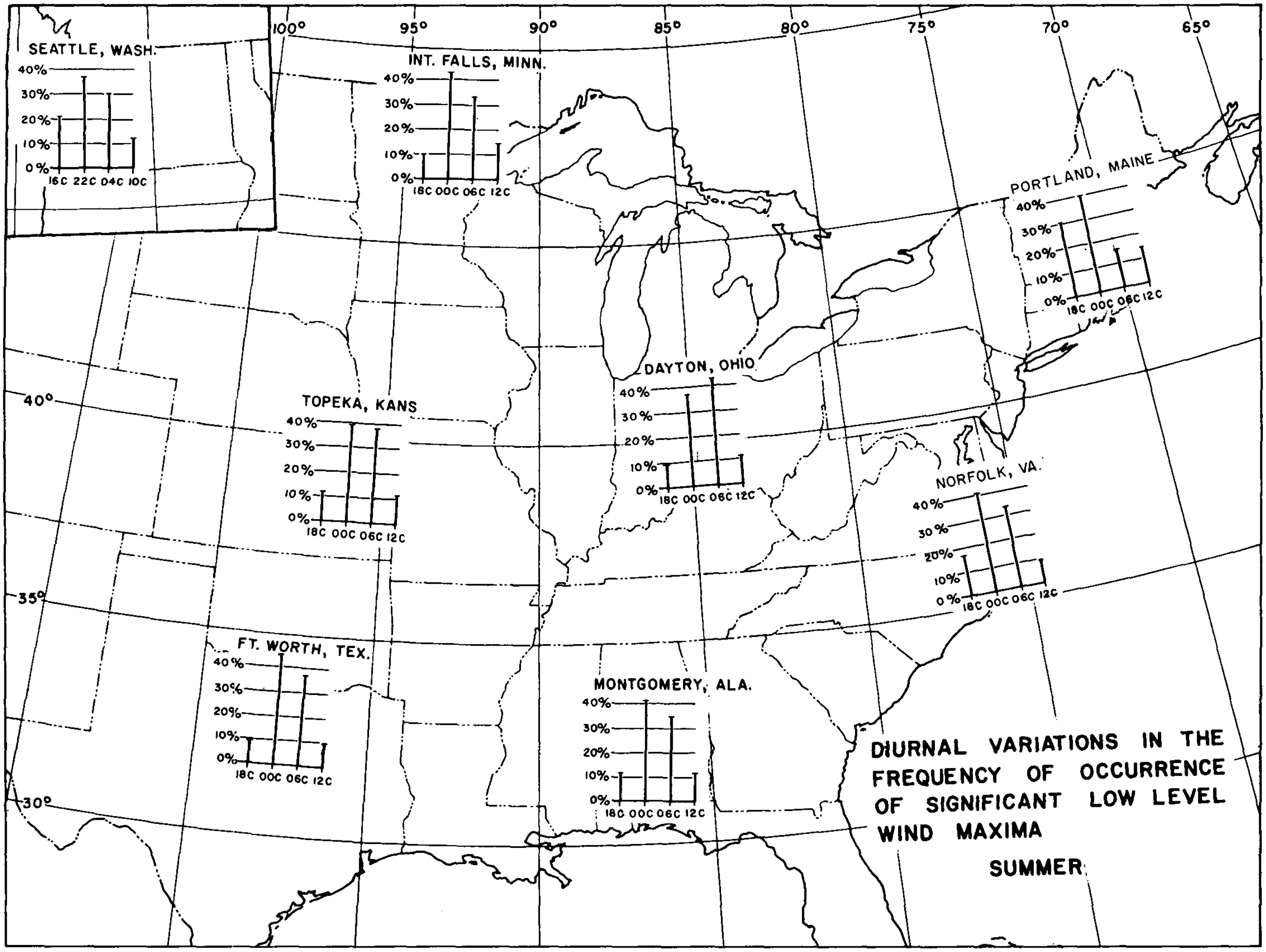

FIGURE 9.—Same as figure 8 except summer months (April 1960 through September 1960).

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 southwest making it possible to sort out southerly jet observations from the total in order to examine the frequency of occurrence of southerly wind maxima across the Great Plains.

A 90° 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 figure 6 except that the greatest wind direction included was always less than 270°.

FREQUENCY OF OCCURRENCE

Figure 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 results, as Wexler suggests, 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 reaching maximum intensity near 30° to 35°N.

The small-scale maximum at Brownsville is difficult to explain. It does not appear to be a reflection of the large-

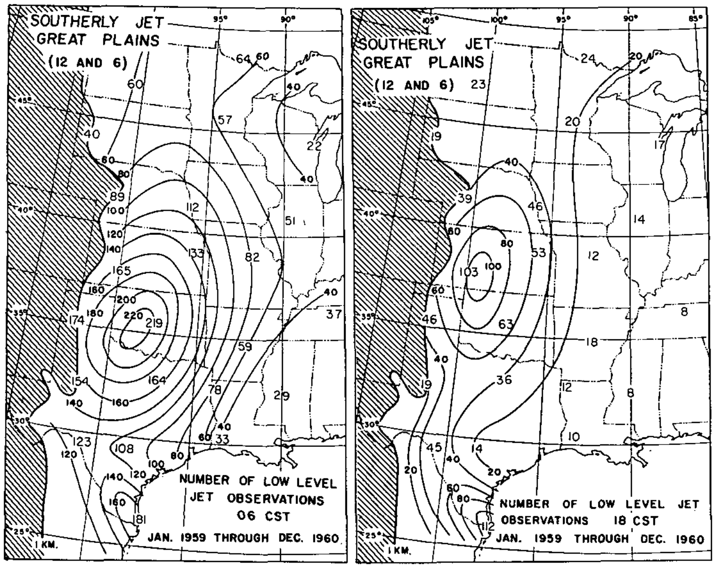

FIGURE 10.—Numbers of Criterion 1 "southerly jet" observations at 06 CST (left) and 18 CST (right). Two years of data.

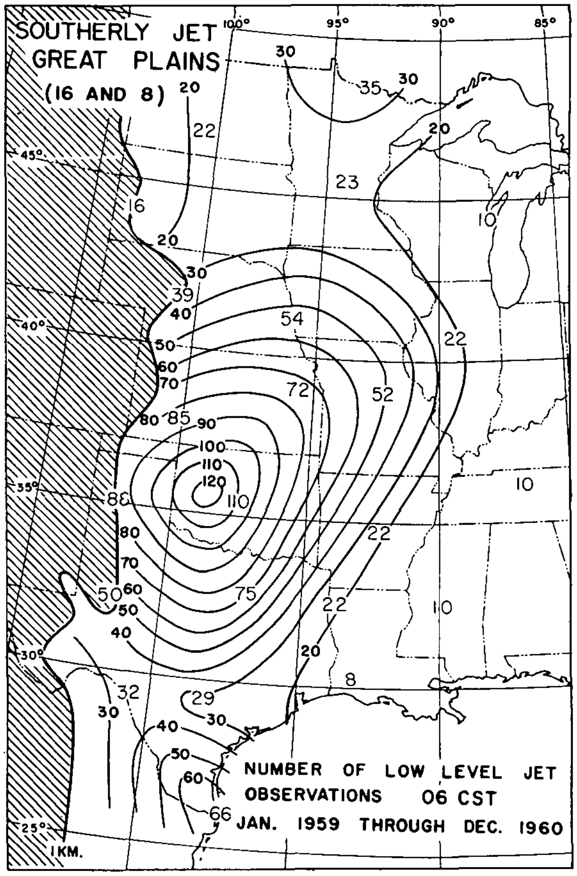

FIGURE 11.—Numbers of Criterion 2 "southerly jet" observations at 06 CST. Two years of data.

TABLE 3.—*Criterion 3 wind maxima at 06* CST *and 18* CST

Station	Number of jet observations	
	06 CST	18 CST
Forth Worth, Tex.	27	3
Oklahoma City, Okla.	43	11
Amarillo, Tex.	48	4
Dodge City, Kans.	51	21
Omaha, Nebr.	24	12

scale southerly jet since probabilities of jet occurrences at Brownsville and at Oklahoma City are completely independent.[5] 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 land-sea breeze effects.

Figure 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 of the patterns disappears on the evening charts. The frequencies of Criterion 3 wind maxima drop 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.

Thom [37] gives tornado probabilities in 1° lat. and long. areas based upon observations from 1953 to 1962. The center of greatest probability is in the middle of Oklahoma—within 50 mi. of the position of the center of maximum southerly jet frequency in figure 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 (Means [25]; Tepper [36]; Curtis and Panofsky [9]).

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 Hydrometeorological Section of the U.S. Weather Bureau [39] covering the years 1906 to 1925 place the region of maximum nocturnal thunder-

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[5] Independence was tested in the following way. Let E_2 be the occurrence of a southerly jet at 06 CST at an arbitrary station. Let E_1 be morning southerly jet occurrence at Oklahoma City. Then, the ratio between the probability of E_2 given that E_1 has occurred and the probability of E_2 is a measure of the correlation between the two events. If

$$\Pr\{E_2|E_1\}/\Pr\{E_2\}=1,$$

the events are independent (Brownlee [7]). If the ratio is significantly greater than (less than) one, E_2 and E_1 are positive (negatively) correlated. Some sample values of this ratio are 2.23 at Topeka, 2.16 at Peoria and Amarillo, 1.26 at San Antonio, 1.03 at Brownsville, and 0.83 at Bismarck. Because of the uncertain extent of the Brownsville frequency maximum, isopleths in south Texas in figures 10 and 11 are only an estimate.

storm 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 figure 11 but roughly along the axis of maximum frequency. Pitchford and London [31] 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 [5] 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.

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.

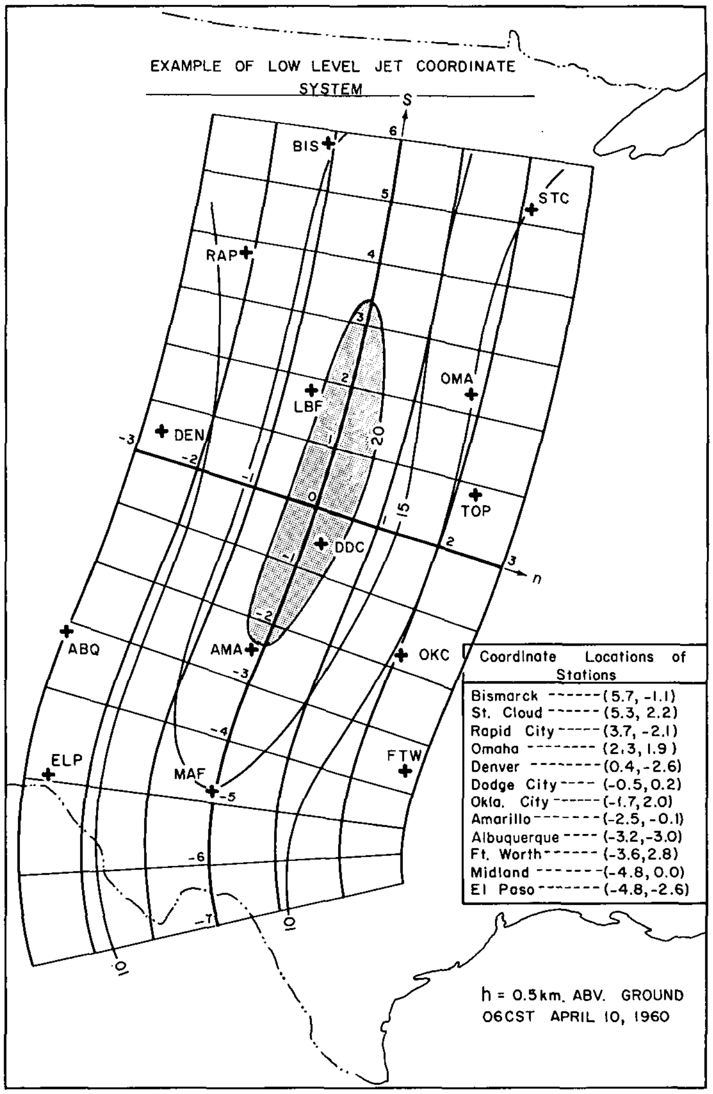
The overall mean of the altitudes of the 06 CST jet observations at all 22 stations was 785 m. The standard deviation among the individual stations was 127 m. If jet altitudes are translated to meters above sea level at each station, the standard deviation more than doubles, indicating that the jet does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

Mean altitudes and altitude distributions indicate that most of the southerly wind maxima will be found 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 1,400-ft. tower near Dallas. 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 observed in the tower measurements.

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 2-yr. period examined, August and September were the months of maximum southerly jet frequency. On the average, approximately 70 percent of the southerly jet observations occurred during the summer months. Two years of data are not enough to establish any definite seasonal trends other than the broad comparison between summer and winter.



Coordinate Locations of Stations	
Bismarck	(5.7, -1.1)
St. Cloud	(5.3, 2.2)
Rapid City	(3.7, -2.1)
Omaha	(2.3, 1.9)
Denver	(0.4, -2.6)
Dodge City	(-0.5, 0.2)
Okla. City	(-1.7, 2.0)
Amarillo	(-2.5, -0.1)
Albuquerque	(-3.2, -3.0)
Ft. Worth	(-3.6, 2.8)
Midland	(-4.8, 0.0)
El Paso	(-4.8, -2.6)

FIGURE 12.—An example of the low level jet coordinate systems 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 standard three-letter designators. Coordinate locations of each station are given at 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.$^{-1}$

5. HORIZONTAL STRUCTURE OF THE SOUTHERLY JET

THE APPROACH

In order to describe the structure of this jet, individual observations of wind speed, temperature, and mixing ratio were averaged in coordinate systems centered on the jet. Low level jet cases were selected from a daily summary of the 2 yr. of southerly jet observations in the Great Plains. Stations were categorized as 0 meaning no jet.

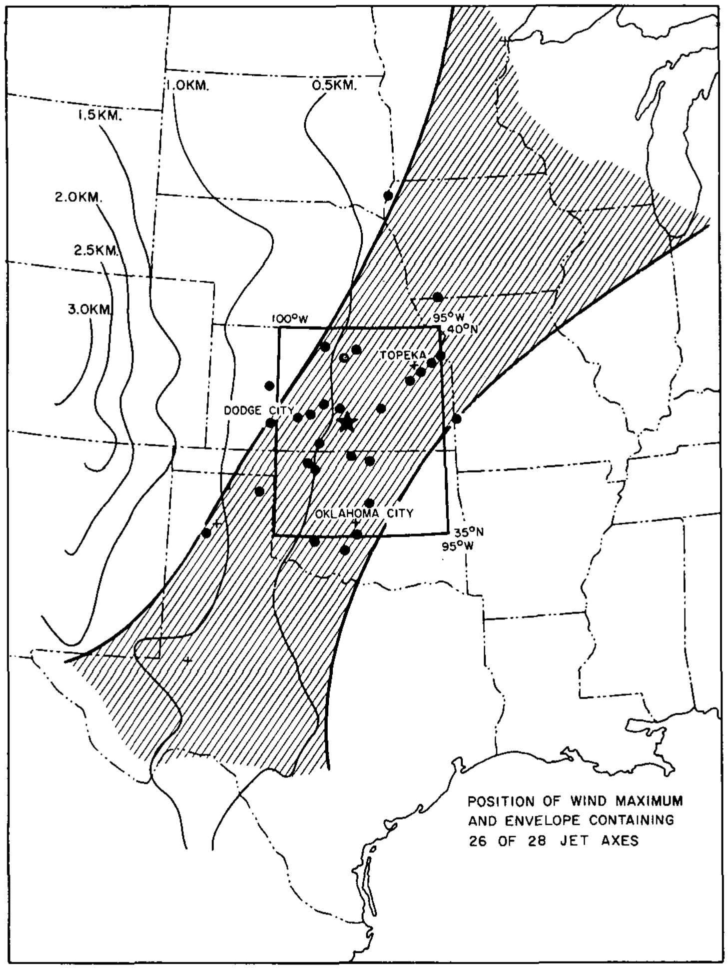


FIGURE 13.—Location of jet core (center of jet coordinate system) in each of 28 cases. A star indicates the median latitude and longitude of the centers. The shaded area includes the low level jet axis in 26 of the 28 cases.

TABLE 4.—*Wind observations in jet coordinate system*

Total possible	Discarded observations			Usable observations
	Missing	Front	No jet	
318	22	13	43	240

9 for missing or incomplete observation, and 1, 2, or 3 corresponding to the particular jet criterion satisfied. 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 six 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.

JET COORDINATE SYSTEM

From the 116 morning jet days, 43 were selected as having one or more stations with Criterion 3 wind maxima and few missing wind observations. Wind and temperature profiles at 06 CST were plotted from ground level to approximately 2.5 km. above the ground 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 with a minimum of subjective analysis. Twenty-eight cases were finally selected where there was a high degree of confidence in the position of the jet core and jet axis. 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 (see fig. 12). Krishnamurti [22] has used the same type of coordinate system to describe mean properties of the subtropical jet stream. Riehl and Fultz [33] used a jet coordinate system in their analysis of laboratory jet streams.

The position of each reporting station in the jet coordinate system was recorded (fig. 12) and wind speeds, temperatures, and mixing ratios on individual observations were averaged within boxes two coordinate units on a side.

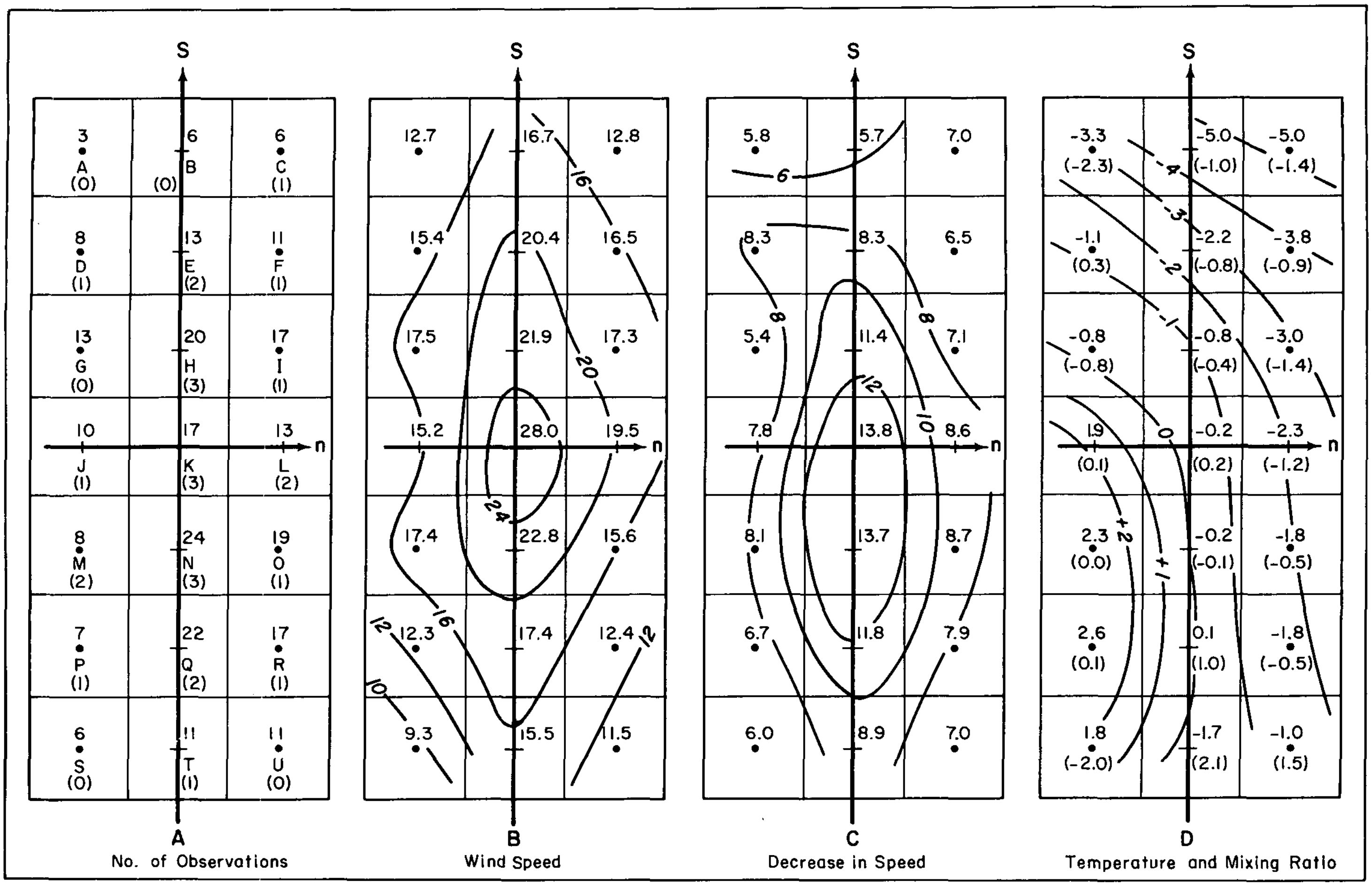
Before discussing the mean patterns, it is worth noting the positions of the center of maximum wind in each of the 28 cases (fig. 13). The median position of the centers is indicated by the star. The shaded area indicates the region enclosed by the envelope of 26 of the 28 analyzed jet axes, showing that the jet typically occupies a fairly narrow range of positions within the central United States.

TWENTY-EIGHT CASE AVERAGES

Of a total of 318 possible observations within the limits of the coordinate system, 240 observations are included in the summaries to follow. Reports were excluded whenever there was a front or trough between the station and the southerly wind maximum or whenever it was impossible to define a level of maximum wind on the particular observation. Disposition of observations is summarized in table 4.

Results are summarized in figure 14. Figure 14A shows the number of observations available within each box. Figures 14B and C show respectively the mean wind speed at the level of maximum wind and the mean decrease in speed above this level. Figure 14D gives the average temperature and moisture patterns at 850 mb.

From figures 14B and C it is possible to define typical region of Criterion 1, 2, or 3 wind maxima. The number in parentheses in each box in figure 14A indicates the criterion number which it satisfies. Criterion 1 is satisfied



A No. of Observations
B Wind Speed
C Decrease in Speed
D Temperature and Mixing Ratio

FIGURE 14.—Twenty-eight case averages in low level jet coordinate system. (A) Number of observations in each box. (B) Wind speeds and (C) Decreases are in m. sec.$^{-1}$ and speeds refer to the level of maximum wind. (D) Temperatures and mixing ratios refer to the 850-mb. level and are departures in °C. or in gm. kgm.$^{-1}$ from the 850-mb. temperature or mixing ratio at the core of the jet.

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.

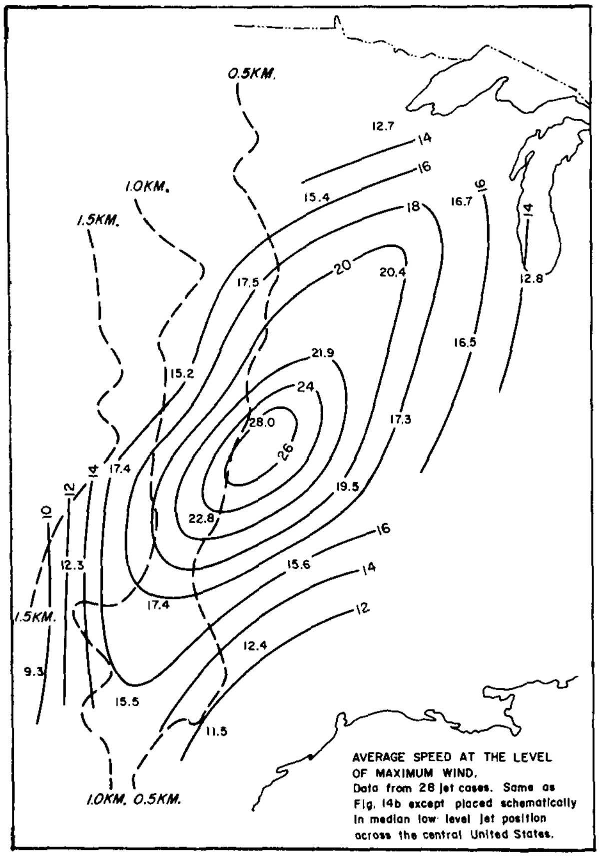
In order to give a better picture of the scale of the low level jet, average speeds are also shown in a schematic mean low level jet coordinate system. In figure 15 the coordinate system has been centered at its median position and the axis is oriented roughly along the median jet axis.

With certain simplifying assumptions, velocity fields in figure 14B can be used to infer approximate values of the divergence in upstream and downstream sections of the jet. If the air streams through the isotach pattern without confluence or difluence, the downstream decrease in speed along the axis of the jet implies a mean convergence in box H (fig. 14A) of -1.3×10^{-5} sec.$^{-1}$ Similarly, the increase in speed on the upstream side of the jet implies, in box N, a net divergence of 1.8×10^{-5} sec.$^{-1}$ Thus, air should be sinking as it moves into the jet maximum and then rising downstream from the jet—leading, as mentioned earlier, to an increased likelihood of nocturnal thunderstorm in the downstream section of the jet.

Decreases in speed above the level of maximum wind (fig. 14C) are greatest along the jet axis and are, in general, larger on the upstream than on the downstream side of the wind maximum. Vertical distances over which the speed decrease took place were not recorded but a typical separation between levels of maximum and minimum wind is 1 to 2 km. When one takes 1.5 km. as an average vertical separation, the negative wind shear above the core of the jet is approximately 10 m. sec.$^{-1}$ km.$^{-1}$ which, if geostrophic, would correspond to a horizontal temperature gradient of more than 3°C. per 100 km.

Figure 14D shows that such temperature gradients do not exist, on the average, in the vicinity of the jet. 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. 13). 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 only about ¼ of the required 10 m. sec.$^{-1}$ km.$^{-1}$

Mixing ratios, handled in the same way as the temperatures, are plotted in parentheses in figure 14D. While



AVERAGE SPEED AT THE LEVEL OF MAXIMUM WIND. Data from 28 jet cases. Same as Fig. 14b except placed schematically in median low level jet position across the central United States.

Figure 15.—Mean isotach pattern (m. sec.$^{-1}$) at the level of maximum wind.

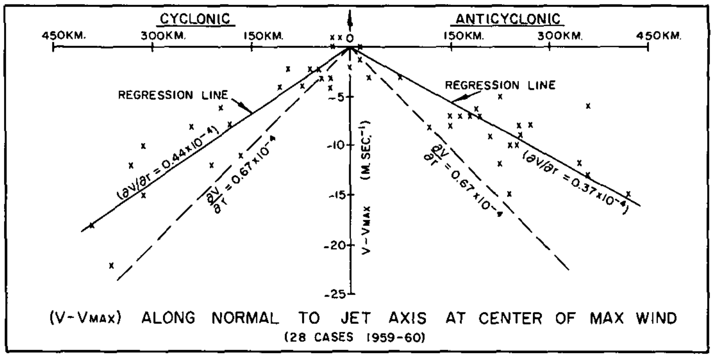


Figure 16.—Decrease in wind speed normal to the jet. The X's indicate the difference between observed wind at stations within approximately 150 km. from the normal to the jet through coordinate center (fig. 12) and the analyzed maximum wind at the jet core. Regression lines through the origin estimate mean wind shear on cyclonic and anticyclonic flanks. Dashed lines give extreme values of shear.

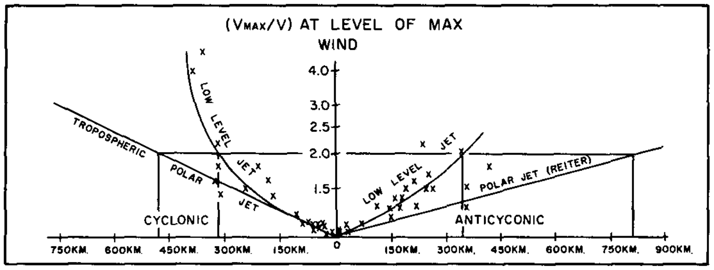


Figure 17.—Ratio between core (V_{max}) and observed wind speed (V) vs. distance from the core of the jet. Same data as in figure 16. Note half-power points for low level jet and for polar jet as given by Reiter [32].

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.

WIND SHEAR ALONG THE LEVEL OF MAXIMUM WIND

Figure 16 shows the decrease in wind speed normal to the jet. The plotted crosses 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 which lie 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 slopes of $+0.44\times10^{-4}$ sec. $^{-1}$ and -0.37×10^{-4} sec. $^{-1}$ respectively. Dashed lines on both sides indicate extreme values of the shear, neglecting points clustered near the core of the jet. 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 [32]).

The ratio V_{max}/V, on a logarithmic scale, versus distance from the jet axis, is shown in figure 17. Included is a similar graph by Reiter [32] constructed from observations near the polar front jet at tropopause level. Curves for the low level jet stream were constructed by eye whereas Reiter fit the data for the high level jet into an exponential relationship, giving a straight line on the semilog 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. Thus, the transverse dimension of the low level jet is approximately ½ that of the typical jet maximum at tropopause level.

Wexler's calculation of the anticyclonic shear to the right of the jet for two assumed values of the total volume transport gives values greater than the Coriolis parameter for a distance of from 100 to 150 km. to the east of the vertical western boundary. Half-power points, as shown in figure 17, are estimated from Wexler's calculations to occur at roughly 140 km. from the core of the jet. In actuality, the anticyclonic shears are definitely much less than the Coriolis parameter and the width of the current is roughly twice that predicted by Wexler. In Wexler's model, however, the gradually sloping terrain is approximated by a vertical wall. With this gross simplification there seems little reason to expect more than qualitative agreement with the picture presented here.

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 limit to the wind velocity at speeds between 55 and 60 kt. It seems to be no accident that cross sections by Wexler of a southerly low level jet show a maximum speed of 55 kt. on each of two mornings; that all three cases studied by Hoecker [17] show maximum jet speeds of 55 kt.; that an example of a boundary layer jet by Blackadar [3] shows a speed of 53 kt. 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 kt. on only four occasions. The maximum speed was between 50 and 60 kt. on 30 of the 43 occurrences.

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 three 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 was to look for the existence of inversions and to compare the height of the top of the inversion with the height of the wind maximum.

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 level of maximum wind was definitely above the inversion top; in 16 cases it was below. In the remaining 15 cases, inversion top and wind maximum appeared to be at the same level on the 06 CST soundings.

The correlation coefficient between the level of maximum wind and inversion top in the 52 cases was 0.53, which is significantly different from 0 but which explains only about ¼ of the variance in jet altitude.

Blackadar [3] showed that the presence of a wind maximum at the top of the inversion acts to control the amount of turbulence and prevent the chaotic breakdown of the inversion. In cases carefully selected to represent situations where strong, undisturbed boundary layer oscillations would be present, he found a much stronger relationship between inversion top and jet level than that presented here.

Blackadar's data indicate, however, that while there may be a tendency for the wind and temperature profile to adopt the more stable configuration it is not necessary that they do. Hoecker [17] and Bonner [5] have shown that strong jet maxima can exist even with nearly adiabatic lapse rates.

Most of the 06 CST profiles examined here showed a shallow, nearly adiabatic layer within the first 100 to 200 m. and a stable layer or inversion above. Detailed studies of the changes in temperatures measured at the 12 levels of the Texas tower (Izumi [20]; Kaimal and Izumi [21]) show that this is a typical temperature profile near sunrise in low level jet situations. The absence of a ground-based inversion in the early morning hours is apparently the result of turbulence generated by strong vertical wind shear beneath the jet (Gifford [14]). As the jet begins to break down near sunrise, there are rapid and pronounced changes in both wind and temperature fields, which fact probably explains the relatively low correlation between inversion top and level of maximum wind on the 06 CST soundings.

TABLE 5.—*Number of jet observations by observation time and station. From a possible 365*

Time (GMT)	Montgomery	Fort Worth	Norfolk	Dayton	Topeka	Portland	International 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

TABLE 6.—*Mean altitudes (in km. above the ground)*

Station	00 GMT	06 GMT	12 GMT	18 GMT
Fort Worth	0.84	0.64	0.70	0.92
Topeka	.84	.72	.78	1.00
International 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

6. DIURNAL VARIATIONS IN CRITERION ZERO JETS

A considerable amount of data was gathered in the original study of Criterion 0 wind maxima which relate 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 [39], Blackadar [3], Hering and Borden [16], and others. The data presented here, however, refer specifically to the winds at the level of maximum wind and cover a larger data sample than has previously been examined.

Results presented are for the eight rawinsonde stations listed in table 1. Four-times-daily observations were examined for a 1-yr. period. A Criterion 0 jet is any wind maximum occurring within the first 1500 m. above the ground where the wind speed decreases by at least 3 m. sec.$^{-1}$ to the next higher minimum or to the 3-km. level, whichever is lower.

TABLE 7.—*Mean speeds, entire year (m. sec.$^{-1}$)*

Station	00 GMT	06 GMT	12 GMT	18 GMT
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
International Falls	11.5	12.6	13.1	12.8
Seattle	11.2	10.4	10.4	10.4
Norfolk	12.0	13.3	12.6	11.6

TABLE 8.—*Speed changes at the level of maximum wind. Paired observations, summer months*

Station	18 CST to 00 CST		00 CST to 06 CST		06 CST to 12 CST	
	Inc.	Dec.	Inc.	Dec.	Inc.	Dec.
Forth Worth	57	7*	29	59	7	41*
Topeka	39	6*	35	37	15	35*
International 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

FREQUENCY OF OCCURRENCE

The number of jet observations at each station at each observation time is listed in table 5. 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, Tex., midnight wind maxima were found on 65 percent of the days for the entire year.

ALTITUDE

Mean altitudes at each of the observation times are summarized in table 6.

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 [16], and Buajitti and Blackadar [7]) 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. (Compare 06 and 12 GMT in table 6.) In a significant percentage of cases, however, wind maxima were actually observed to descend during the same period (see also Novozhilov [30]). For example, at Fort Worth, Tex., 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 6-hr. period on 76 days and decreased in 35. Cases were not included in which there were obvious changes in air mass between successive observation times.

While little that is definitive can be said about the changes in altitude between 06 GMT and 12 GMT, 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 7. It had been expected that, if Blackadar's hypothesis was 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 at the various observation times. The type of variation expected is apparent at Fort Worth, Topeka, and Norfolk. At other stations, however, the strongest wind speeds occur with about equal regularity on daytime and nighttime observations.

By considering only "paired" jet observations (cases in which wind maxima were recorded on at least two successive wind observations), it is possible to obtain a sample of relatively independent data which gives a more direct 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. All cases where an obvious frontal passage occurred during the 6-hr. period or where wind maxima were recorded at several levels on the same observation were ignored. In table 8, paired observations have been classified as representing simply an increase or a decrease with time in the wind speed. Data are presented for the summer months alone. An asterisk indicates that the indicated tendency is statistically significant at a 0.01 level of probability.[6]

At each of the stations in table 8, 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, how-

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[6] The data were first tested for independence by computing the number of runs of elements of two different types (see, for example, Brownlee [6]). *P* values were then determined 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.

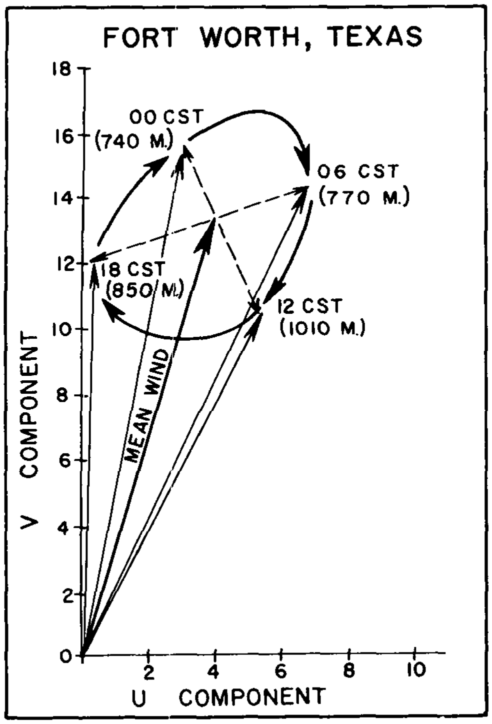

Figure 18.—Vector mean winds on 16 summer days with Criterion 0 wind maxima on all four daily observations. Mean altitudes in m. above the ground at each observation time are indicated in parentheses. Note the rotation about the mean wind.

ever, 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, Tex., however, there appears to be a clear tendency for maximum speeds to occur on the 00 CST observation, suggesting that the average time of maximum wind speed is between midnight and 03 CST. At Topeka, Kans., the distribution of increases and decreases is about even and at International Falls, Minn., there is a slight tendency towards increasing wind speeds, suggesting, in this case, a shift in the average time of maximum wind to somewhere between 03 CST and 06 CST. The same shift towards later times with increasing latitude is indicated by a comparison of the nighttime paired observations at Montgomery, Ala., and at Dayton, Ohio.

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

Results from a comparison of paired observations in winter were similar to those in table 8. 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 0.01 level of probability.

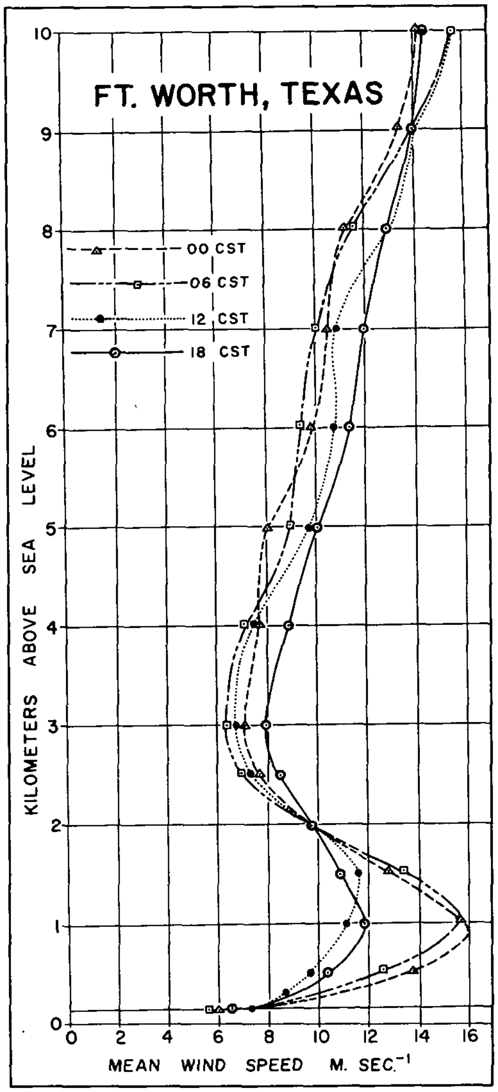

Figure 19.—Mean wind speed profiles for same 16 summer days as in figure 17. Note the strong jet profiles at 00 and 06 CST and the crossover point at 2.0 km.

The failure of these oscillations to appear in the mean data from stations other than Fort Worth and Topeka (table 7) may be the result of daytime turbulence. The shear or speed decrease criterion imposed here was only 3 m. sec.$^{-1}$ If the winds are strong, turbulence induced by surface heating may introduce small-scale variations in wind speed which temporarily exceed the 3 m. sec.$^{-1}$ criterion, leading to a bias towards high speed, low shear wind maxima on the afternoon sounding.

FURTHER EXAMINATION OF DIURNAL OSCILLATIONS IN WIND SPEED AT FORT WORTH, TEX.

Figure 18 is a plot of the vector mean winds on 16 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.

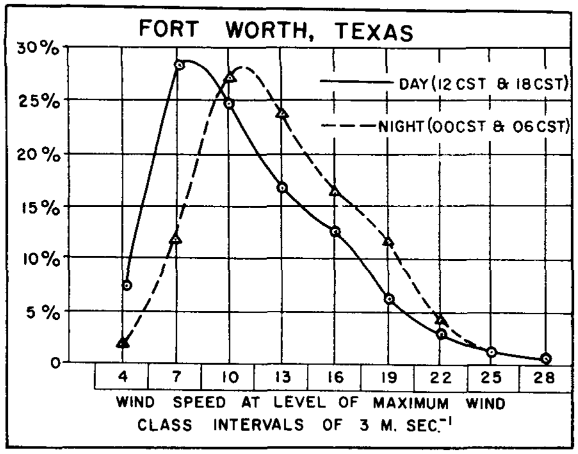

Figure 20.—Percentage of total Criterion 0 jet observations falling within 3-m. sec.$^{-1}$ class intervals of speed at the level of maximum wind; 457 nighttime observations and 281 during the day. Note the higher speeds on nighttime observations.

Similar diagrams have been constructed by Blackadar [3] and Hering and Borden [16]. The mean amplitude of the **V**′ vector in figure 18 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 figure 19 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 (Buajitti and Blackadar [7] and Hering and Borden [16]) on the vertical extent of the nighttime shift towards higher wind speeds in this area.

Wind speeds at jet level are essentially the same at 12 CST and 18 CST and again at 00 CST and 06 CST. In figure 20 these observation times were combined to give frequency distributions of wind speed for the entire year on "daytime" and "nighttime" jet observations. The diurnal oscillation in speed is apparent as a simple linear translation of the distribution towards higher speeds at night.

7. SUMMARY AND CONCLUSIONS

The southerly low level jet has been isolated as a phenomenon occurring at about 800 m. above the ground in the south-central United States. Similar wind maxima are observed on individual soundings from stations 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 areas. 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 occurrences. 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 strong pressure gradient across the Great Plains with a smooth, uninterrupted flow of air northward from the Gulf of Mexico.

The importance of a diurnal wind oscillation in producing the wind maxima is clear from the ratios between nighttime and daytime jet frequency and from the study of Criterion 0 wind maxima at Fort Worth. This oscillation at least superficially resembles the inertial oscillation proposed by Blackadar. However, as Holton has stated, it is difficult to see why low level jets should be so much more common in the Great Plains than in other regions if they result solely from the type of oscillation which Blackadar describes. In this connection, data presented here fail to indicate any tendency for an inertial period in the oscillation.

There seems to be a need at this point for a more general explanation of the low level jet. Different hypotheses offered thus far have emphasized different physical processes: diurnal oscillations in eddy viscosity, diurnal changes in temperature fields over sloping terrain, the blocking of the large-scale flow by the Rocky Mountains. Observational studies of the type presented here cannot clearly show which of these effects is most important and how they interact in a particular region to produce the jet. The only definitive answer is likely to come from numerical integration of three-dimensional models which include viscosity, and which allow for time variations in both ageostrophic and geostrophic components of the wind. Since the diurnal oscillation of the wind disappears near 2 km., it may be possible to use this level as an upper boundary. However, the existence of diurnal oscillations in the middle and upper troposphere (Hering and Borden [16]) implies some interaction between the boundary layer and levels above (Darkow and Thompson [10]).

The feasibility of this approach has been demonstrated by Estoque [11] who integrated a system of equations for the boundary layer, producing, incidentally, a low level jet near 700 m. above the ground.

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REFERENCES

1. H. Arakawa, "Characteristics of the Low-Level Jet Stream," *Journal of Meteorology*, Vol. 13, No. 5, Oct. 1956, pp. 504–506.
2. M. L. Barad, "Low-Altitude Jet Streams," *Scientific American*, Vol. 205, No. 2, New York, Aug. 1961, pp. 120–131.
3. A. K. Blackadar, "Boundary Layer Wind Maxima and Their Significance for the Growth of Nocturnal Inversions," *Bulletin of the American Meteorological Society*, Vol. 38, No. 5, May 1957, pp. 283–290.

4. W. Bleeker and M. J. Andre, "On the Diurnal Variations of Precipitation, Particularly Over Central U.S.A., and Its Relation to Large-Scale Orographic Circulation Systems," *Quarterly Journal of the Royal Meteorological Society*, Vol. 77, No. 332, Apr. 1951, pp. 260–271.
5. W. Bonner, "Case Study of Thunderstorm Activity in Relation to the Low-Level Jet," *Monthly Weather Review*, Vol. 94, No. 3, Mar. 1966, pp. 167–178.
6. K. A. Brownlee, *Statistical Theory and Methodology in Science and Engineering*, John Wiley and Sons, Inc., New York, 1960, 570 pp.
7. K. Buajitti and A. K. Blackadar, "Theoretical Studies of Diurnal Wind-Structure Variations in the Planetary Boundary Layer," *Quarterly Journal of the Royal Meteorological Society*, Vol. 83, No. 358, Oct. 1957, pp. 486–500.
8. J. G. Charney, "The Gulf Stream as an Inertial Boundary Layer," *Proceedings of the National Academy of Sciences*, Vol. 41, No. 10, University of Chicago Press, Oct. 1955, pp. 731–740.
9. R. C. Curtis and H. A. Panofsky, "The Relation Between Large-Scale Vertical Motion and Weather in Summer," *Bulletin of the American Meteorological Society*, Vol. 39, No. 10, Oct. 1958, pp. 521–531.
10. G. L. Darkow and O. E. Thompson, "Diurnal Oscillations of the Tropospheric Wind Field Above a Low-Level Jet," *Journal of the Atmospheric Sciences*, Vol. 25, No. 1, Jan. 1968, pp. 39–46.
11. M. Estoque, "A Numerical Model of the Atmospheric Boundary Layer," *Journal of Geophysical Research*, Vol. 68, No. 4, Feb. 1963, pp. 1103–1113.
12. J. R. Gerhardt, "An Example of a Nocturnal Low-Level Jet Stream," *Journal of the Atmospheric Sciences*, Vol. 19, No. 1, Jan. 1962, pp. 116–118.
13. J. R. Gerhardt, "Mesoscale Association of a Low-Level Jet Stream With a Squall-Line: Cold-Front Situation," *Journal of Applied Meteorology*, Vol. 2, No. 1, Feb. 1963, pp. 49–55.
14. F. A. Gifford, Jr., "The Breakdown of a Low-Level Inversion Studied by Means of Detailed Soundings With a Modified Radiosonde," *Bulletin of the American Meteorological Society*, Vol. 33, No. 9, Nov. 1952, pp. 373–379.
15. B. Haurwitz and J. Austin, *Climatology*, McGraw-Hill Book Co., Inc., New York, 1944, 410 pp.
16. W. S. Hering and T. R. Borden, Jr., "Diurnal Variations in the Summer Wind Field Over the Central United States," *Journal of the Atmospheric Sciences*, Vol. 19, No. 1, Jan. 1962, pp. 81–86.
17. W. H. Hoecker, Jr., Three Southerly Low-Level Jet Systems Delineated by the Weather Bureau Special Pibal Network of 1961," *Monthly Weather Review*, Vol. 91, No. 10–12, Oct.–Dec. 1963, pp. 573–582.
18. W. H. Hoecker, Jr., "Comparative Physical Behavior of Southerly Boundary-Layer Wind Jets," *Monthly Weather Review*, Vol. 93, No. 3, Mar. 1965, pp. 133–144.
19. J. R. Holton, "The Diurnal Boundary Layer Wind Oscillation Above Sloping Terrain," *Tellus*, Vol. 19, No. 2, 1967, pp. 199–205.
20. Y. Izumi, "The Evolution of Temperature and Velocity Profiles During Breakdown of a Nocturnal Inversion and a Low-Level Jet," *Journal of Applied Meteorology*, Vol. 3, No. 1, Feb. 1964, pp. 70–82.
21. J. C. Kaimal and Y. Izumi, "Vertical Velocity Fluctuations in a Nocturnal Low Level Jet," *Journal of Applied Meteorology*, Vol. 4, No. 5, Oct. 1965, pp. 576–584.
22. T. N. Krishnamurti, "The Subtropical Jet Stream of Winter," *Journal of Meteorology*, Vol. 18, No. 2, Apr. 1961, pp. 172–191.
23. J. Kuettner, "The Band Structure of the Atmosphere," *Tellus*, Vol. 11, No. 3, Aug. 1959, pp. 267–294.
24. H. Lettau, "1954: Graphs and Illustrations of Diverse Atmospheric States and Processes Observed During the Seventh Test Period of the Great Plains Turbulence Field Program," *Occasional Report* 1, Atmospheric Analysis Laboratory, Air Force Cambridge Research Center, Mass.
25. L. L. Means, "On Thunderstorm Forecasting in the Central United States," *Monthly Weather Review*, Vol. 80, No. 10, Oct. 1952, pp. 165–189.
26. L. L. Means, "A Study of the Mean Southerly Wind-Maximum in Low Levels Associated With a Period of Summer Precipitation in the Middle West," *Bulletin of the American Meteorological Society*, Vol. 35, No. 4, Apr. 1954, pp. 166–170.
27. G. W. Morgan, "On the Wind-Driven Ocean Circulation," *Tellus*, Vol. 8, No. 3, Aug. 1956, pp. 301–320.
28. C. W. Newton, "Mechanisms of Circulation Change During a Lee Cyclogenesis," *Journal of Meteorology*, Vol. 13, No. 6, Dec. 1956, pp. 528–539.
29. C. W. Newton, "Synoptic Comparisons of Jet Stream and Gulf Stream Systems," *Technical Report* No. 1, Office of Naval Research, Contract Nonr. 2121 (10), NR 082–161, University of Chicago, 1959, 34 pp.
30. N. I. Novozhilov, "Troposfernye Mezostrvi" [Tropospheric Mesocurrents], *Seriia Geofizicheskaia* No. 2, Akademiia Nauk SSSR, Izvestiia, Moscow, Feb. 1961, pp. 334–336.
31. K. L. Pitchford and J. London, "The Low-Level Jet as Related to Nocturnal Thunderstorms Over Midwest United States," *Journal of Applied Meteorology*, Vol. 1, No. 1, Mar. 1962, pp. 43–47.
32. E. R. Reiter, *Jet Stream Meteorology*, University of Chicago Press, 1963, 515 pp.
33. H. Riehl and D. Fultz, "The General Circulation in a Steady Rotating-Dishpan Experiment," *Quarterly Journal of the Royal Meteorological Society*, Vol. 84, No. 362, Oct. 1958, pp. 389–417.
34. W. E. Sangster, "Diurnal Surface Geostrophic Wind Variations Over the Great Plains," *Proceedings of the Fifth Conference on Severe Local Storms, St. Louis, Mo., Oct. 19–20, 1967*, Greater St. Louis Chapter, American Meteorological Society, 8 pp.
35. Staff Members, U.S. Weather Bureau, National Severe Storms Project, Kansas City, Mo., "Environmental and Thunderstorm Structures as Shown by National Severe Storms Project Observations in Spring 1960 and 1961," *Monthly Weather Review*, Vol. 91, No. 6, June 1963, pp. 271–292.
36. M. Tepper, "On the Generation of Pressure-Jump Lines by the Impulsive Addition of Momentum to Simple Current Systems," *Journal of Meteorology*, Vol. 12, No. 4, Aug. 1955, pp. 287–297.
37. H. C. S. Thom, "Tornado Probabilities," *Monthly Weather Review*, Vol. 91, No. 10–12, Oct.–Dec. 1963, pp. 730–736.
38. U.S. Weather Bureau and U.S. Corps of Engineers, "Thunderstorm Rainfall," *Hydrometeorological Report* No. 5, Parts 1 and 2, Waterways Experiment Station, Vicksburg, Miss., 1947, 331 pp. plus 155 figures.
39. A. Wagner, "Uber die Tageswinde in der freien Atmosphäre" [Concerning the Daily Wind in the Free Atmosphere], *Beitrage Zur Physik der freien Atmosphäre* Vol. 25, Akademesche Verlagsgesellschaft M.B.H., Leipzig, 1939, pp. 145–170.
40. H. Wexler, "A Boundary Layer Interpretation of the Low-Level Jet," *Tellus*, Vol. 13, No. 3, Aug. 1961, pp. 368–378.

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