THREE SOUTHERLY LOW-LEVEL JET SYSTEMS DELINEATED BY THE WEATHER BUREAU SPECIAL PIBAL NETWORK OF 1961

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ABSTRACT

For the first time in meteorological history the broad aspects of the southerly low-level jet over the Western Plains have been studied in fine detail both in time and space. This was accomplished in the spring of 1961 by means of a line of 13 pibal stations established between Amarillo, Tex., and Little Rock, Ark. Twenty-five consecutive hourly observations were taken at each station on a total of five different 24-hr. periods in April, May, and June. Three of the observational periods were analyzed and the jet characteristics are described. High pressure cells east of the Great Plains, whether of polar or tropical origin, produced low-level southerly jet systems. Jet speed maxima occurred between 300 and 800 m. above the ground (generally well below the 850-mb. level) and were often found in several horizontally-arranged cells. By day the jet was incoherent (with one exception) and speeds were sub-geostrophic, while at night the jet was well organized and coherent and speed maxima were as high as 1.95 times the sea level geostrophic speed. The jet lifted over mountainous regions and over intruding mesosystems. On those nights with surface inversions the speed maxima were lower in elevation and required a smaller pressure gradient for a given maximum nighttime speed than when lapse conditions existed, but their elevation apparently had no correlation with the height of the inversion itself.

Blackadar's theory of the inertial oscillation for producing the low-level nocturnal jet is easily applicable for the practicing forecaster, but Wexler's inertial boundary layer interpretation predicts the jet by day as well as by night on a basic southerly current. Both theories seemed to apply at times during the existence of the jet systems described here.

1. INTRODUCTION

Interest in the southerly low-level jet has increased considerably in recent years. This is possibly due to an increase in nighttime private flying for which safety has increased considerably with the advent of the light twin-engine airplane. Among the first to study this phenomenon from a meteorological standpoint were Means [7] for the purpose of forecasting nighttime thunderstorm rains in the Midwest, and Blackadar [2] for preventing aircraft landing accidents due to large values of wind shear near the ground. Despite the common terminology, their viewpoints were essentially different, however. For other reasons, Charney [3] and Morgan [8] proposed the inertial boundary layer theory for the relatively high-speed current of the Gulf Stream and later Newton [9] suggested the similarity between the Gulf Stream and the low-level jet system in the narrow concentration of momentum and the location just east of a meridional barrier—the slopes leading to the Rocky Mountains for the atmospheric jet and the continental shelf for the Gulf Stream. Polson [12] called the jet a "Sunrise Wind" in a popular aviation magazine and suggested its use as a fuel saver for northward flights and its avoidance for flights to the south. Wexler [13] applied the inertial boundary-layer theory of Charney and Morgan on ocean currents to the southerly low-level jet and in a discussion with the author indicated that the theory would apply to flow along the Great Plains from the north as well, and produce a northerly low-level jet. From a flyer's point of view Durosko [6] wrote of a personal experience with the southerly jet wherein he completed a nighttime airplane trip from New Orleans to Cleveland via Joliet of 1180 mi. with a no-wind, no-reserve fuel range of only 1050 mi. He flew at about 2500 ft. elevation and claims to have saved 31 gallons of fuel out of 119 gallons needed for the no-wind trip.

Undoubtedly some augmentation of the southerly low-level wind field exists in the western plains area under suitable synoptic conditions. The purpose of this paper is to describe three special detailed observations of the southerly augmented wind and to examine the characteristics of the jet system.

Now for the first time we have been able to study the low-level jet of the Great Plains in considerable detail in both time and space.

2. THE SOUTHERLY JET OBSERVATIONAL NETWORK

Meteorological interest in the Midwest nocturnal southerly jet was revived in 1961 by the late Dr. Harry Wexler when he published a paper [13] on the subject

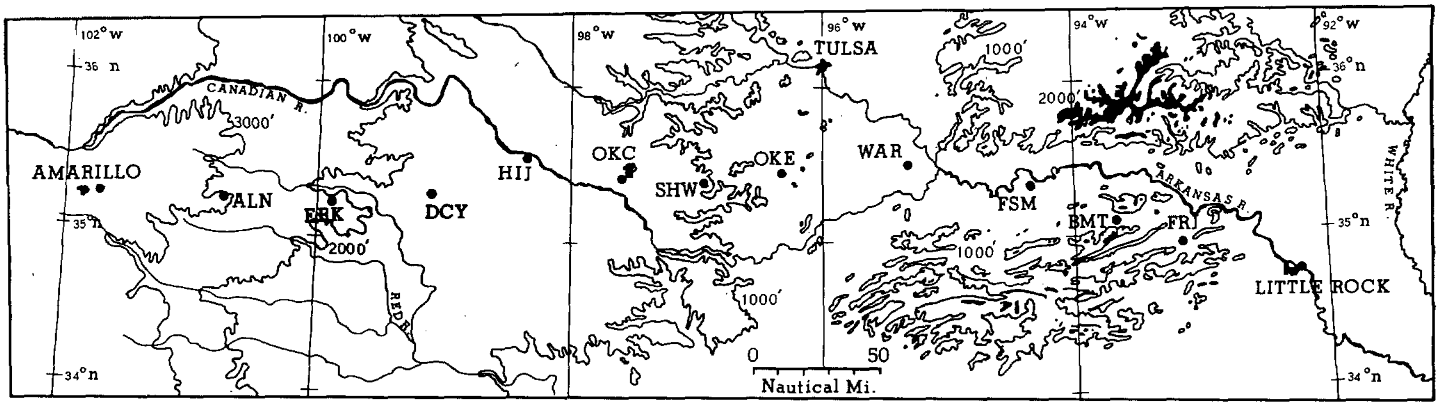

FIGURE 1.—A topographical map of the pibal cross-section region showing elevations at 1,000-ft. intervals. Note the extremely mountainous area between 92° and 96° W. where blacked-in areas are above 2,000 ft. m.s.l. See table 1 for the station code identifiers.

using 1951 pibal data to verify diurnal wind speed changes in the jet system. Dr. Wexler's ultimate objective was to seek a dynamic cause for the onset of Midwest nocturnal thunderstorms. The same year, chiefly under his instigation, a line of 13 closely spaced pibal stations was established from Little Rock, Ark., to Amarillo, Tex., to examine the large-scale properties of the jet system. In the months of April, May, and June 1961, five days of observations were taken there by the Weather Bureau National Severe Storms Project. They consisted of 25 consecutive hourly simultaneous pibal runs at each of the 13 stations with an attempt to reach at least 3 km. elevation before terminating the flight. At the regular upper air observational hours use was generally made of the regular rawinsonde equipment at Amarillo, Oklahoma City, and Little Rock. It was the intent of Dr. Wexler to have observations taken when the Bermuda High was well developed westward across the Gulf Coast and when there were no fronts or squall lines in the vicinity of the observational line. As it turned out one observational period was polluted by a front and another by a large meso-High developed by some thunderstorms. The remaining three observations, April 22–23, May 28, and May 30, are considered in this study.

The line of observation stations extended nearly 860 km., horizontally for an average spacing of 71.5 km. Mean sea level altitudes ranged from 265 ft. (81 m.) at Little Rock to 3604 ft. (1098 m.) at Amarillo. Terrain features varied from the hilly and mountainous regions of Arkansas and eastern Oklahoma to the smooth plains extending from Warner, Okla., to Amarillo, Tex. A map of the region showing these features and the station locations is displayed as figure 1. The stations are listed on the map by code letters which are identified in table 1.

TABLE 1.—*Special pibal network stations, code designations, and locations*

Station	Code	Location				Elevation
		°	′ N.	°	′ W.	(m.)
Amarillo, Tex.	AMA	35	14	101	42	1098
Alanreed, Tex.	ALN	35	13	100	44	910
Erick, Okla.	ERK	35	13	99	53	631
Dill City, Okla.	DCY	35	17.5	99	08	576
Hinton Junction, Okla.	HIJ	35	32	98	21	454
Oklahoma City, Okla.	OKC	35	24	97	36	392
Shawnee, Okla.	SHW	35	22	96	56	331
Okemah, Okla.	OKE	35	26	96	19	275
Warner, Okla.	WAR	35	30	95	17	175
Fort Smith, Ark.	FSM	35	20	94	22	141
Blue Mountain, Ark.	BMT	35	07	93	42.5	129.5
Fourche Junction, Ark.	FRJ	34	51.5	93	09	134
Little Rock, Ark.	LIT	34	44	92	14	81

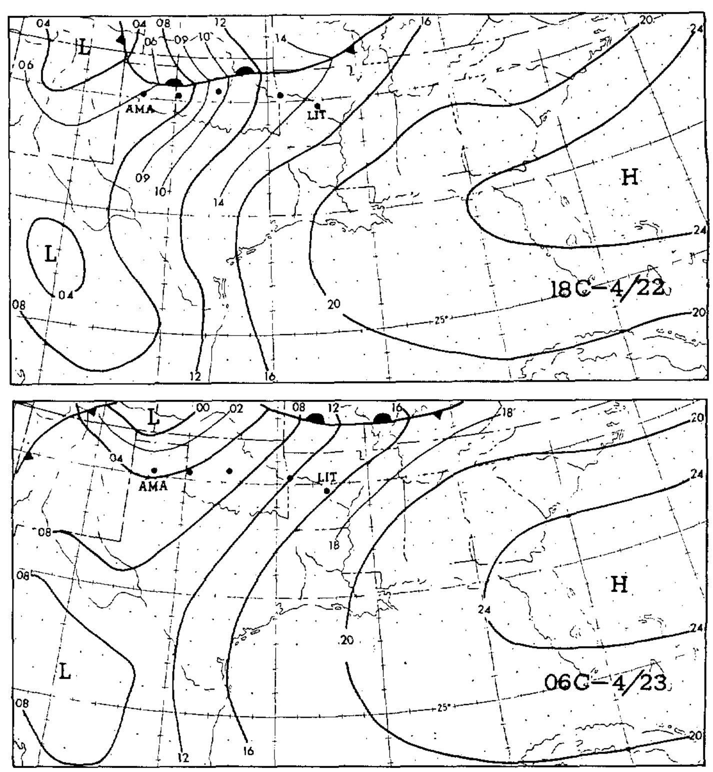

FIGURE 2.—Sea level synoptic maps for 1800 CST April 22 and 0600 CST, April 23, 1961, with some of the pibal observation stations indicated. The extension of the Bermuda High into the Gulf of Mexico is evident.

Single-theodolite-type observations were used and data were punched on IBM cards and processed by the IBM 7090. Speeds (total and components) were averaged over 1-minute intervals instead of the 2-minute method of convention giving an apparent first level speed about 110 m. above the ground. Surface winds were estimated by the observing station personnel.

The 30-gm. balloon with a nominal ascent rate of 180 m./min. was used almost exclusively. Amarillo used the 100-gm. balloon with an ascent rate of 300 m./min. Other exceptions were at Amarillo, Oklahoma City, and Little Rock, where rawinsonde equipment was generally used at the regular upper-air observation times.

3. THE JET CROSS-SECTIONS

For the purpose of studying the large-scale time and space fluctuations of the low-level jet, cross-sectional charts were constructed using a schematic terrain profile on which were located the stations according to their east–west spacing and their elevations. (As an example see fig. 3.) The southerly-component isotachs of wind speed

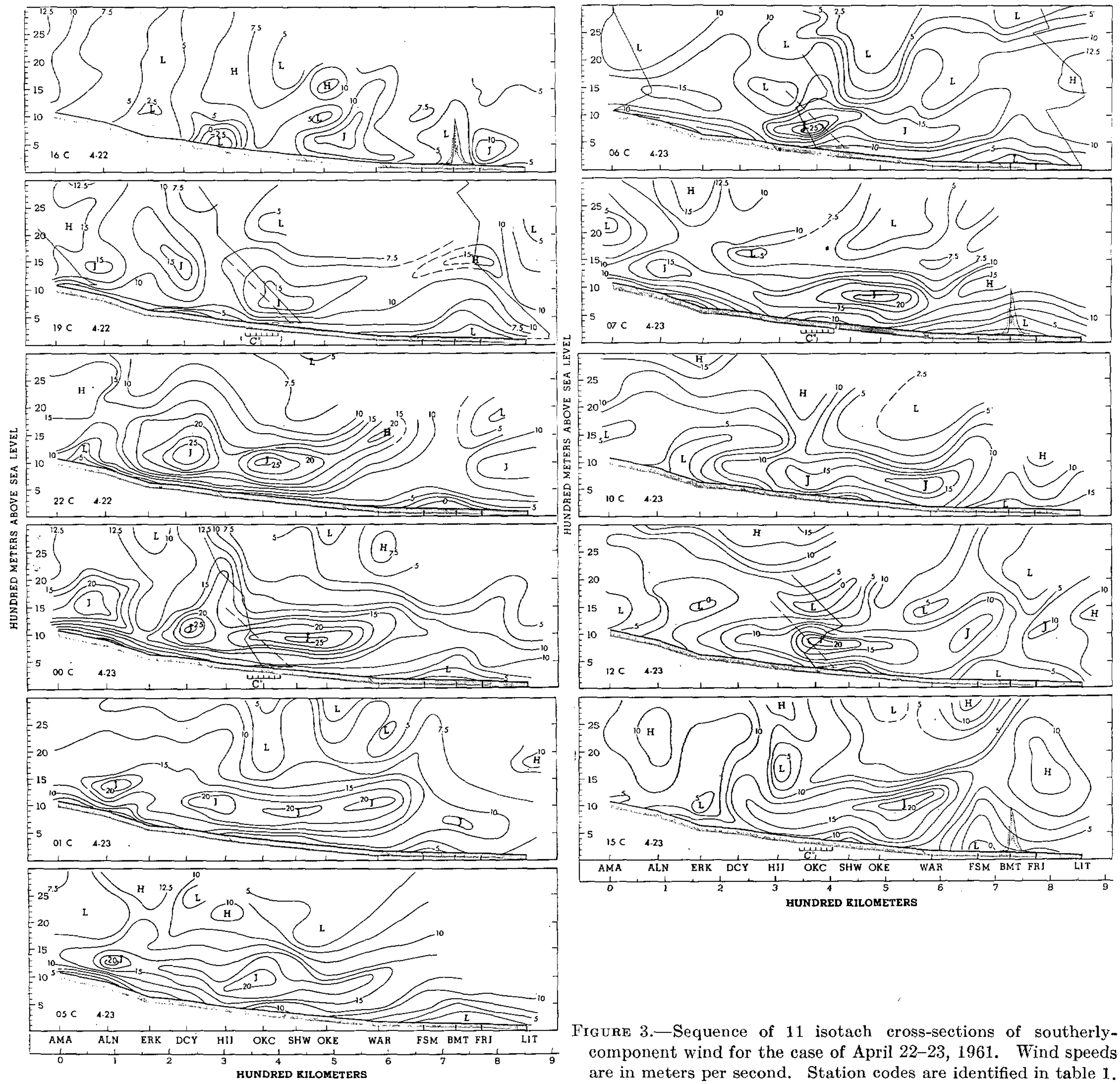

Figure 3.—Sequence of 11 isotach cross-sections of southerly-component wind for the case of April 22–23, 1961. Wind speeds are in meters per second. Station codes are identified in table 1.

are drawn for every 2.5 m./sec. (4.85 kt.). The letter "J" locates the positions of the low-level jet isotach maxima, "H" locates other relatively high speed regions, and "L" shows low and northerly-component speed areas. The vertical thermal structure over Amarillo, Oklahoma City, Little Rock, and sometimes Fort Smith, Ark., is shown at or near standard observation times. The relative temperature scale for the soundings is shown several times in each cross-section figure, and the slope of constant potential temperature is shown by the dashed line near the lapse rate curve. The Tinker AFB observation was used instead of Oklahoma City at 0000 and 1200 CST. Also shown occasionally are the schematic profiles of two mountains just 5 km. northeast (solid line) and 11 km. south (dotted line) of the station at Blue Mountain.

One of the three observational periods used here ran from 1500 CST until 1500 CST the next day; the other two extended from midnight to midnight.

Throughout the paper it is to be understood that heights of the jet system elements, mentioned in the text, are above the ground for the region under discussion.

THE CASE STUDY OF APRIL 22–23, 1961

The synoptic picture attending the observational period 1500 CST April 22 to 1500 CST April 23 is represented by figure 2, where the sea level isobaric pattern is shown for 1800 CST April 22 and 0600 CST April 23. The nominal condition for the establishment of the low-level jet, that is, the extension of the Bermuda High westward along the Gulf Coast and into southern Texas, was realized for this period. This assured that a large volume of trade wind air would flow into the Texas-Oklahoma area when deflected by the mountains of Central America and Mexico. No fronts intruded into the pibal cross-section during this observation and the geostrophic wind remained from south-southwest to southwest.

Figure 3 contains some of the hourly cross-section observations of the southerly component of the wind in this period. Following through the cross-sections, one can see the development of a strong, low-level jet system, with several speed maxima by 2200 CST continuing past midnight. Although the low-level thermal structure was more stable (represented at Oklahoma City) at midnight, no surface inversion existed. The speed maxima at the Dill City and Oklahoma City areas at 2200 CST increased to $1\frac{5}{8}$ times the value at 1900 CST, in line with the increase of the sea level pressure gradient there. Even though the sea level pressure gradient increased between 1800 CST on the 22d and 0000 CST on the 23d, the maximum real total wind increased faster and so was 115 percent of the sea level geostrophic total wind at 0000 CST 23d. Use was made of total vector magnitudes in these comparisons because the southerly components of the real and geostrophic winds were not proportional to the total real and geostrophic winds. It is interesting to note that the jet maximum at Shawnee was neatly bracketed by the inversion layer represented at Oklahoma City at 0000 CST.

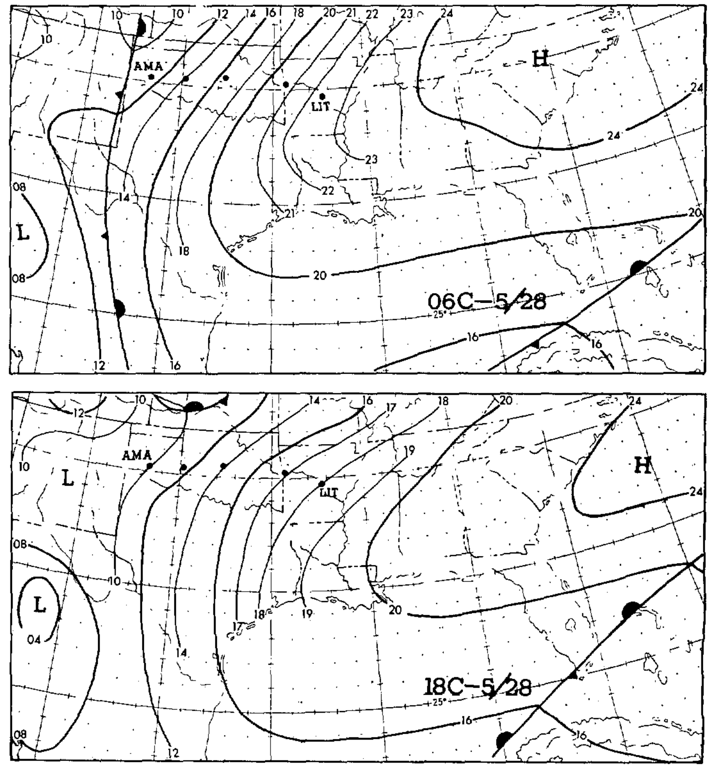

FIGURE 4.—Sea level synoptic maps for 0600 and 1800 CST, May 28, 1961. The high pressure cell involved is of polar origin.

The cross-section for 0100 CST on the 23d shows the rapid change in isotach pattern that occurred in the period of 1 hour following 0000 CST. Such changes were typical in all three cases. Note that the strong jet over Oklahoma City at 0600 CST was in the lapse region of the upper-air sounding halfway between the ground and the base of the high-level inversion. Although a thick inversion layer moved in over Oklahoma City by 1200 CST, the jet maximum there did not change elevation significantly, hence its position was again in an inversion layer. The speed of the jet maximum at 1200 CST was just about equal to that of the geostrophic wind.

It is thought significant that the jet system did not break up after sunrise (0549 CST at Oklahoma City), but continued on to 1500 CST on the 23d. For this 24-hr. period the jet speed maximum had no tendency to follow the top of the atmospheric stable layer. Further, it is evident that a super-geostrophic nocturnal low-level jet can exist without a surface inversion and a jet system can exist well into the afternoon.

It is suggested that the jet system did not break up after sunrise because of the observed overcast cloudiness in the Oklahoma City–Fort Smith area. However, the ceilings were not lower than 12,000 ft. at Oklahoma City or 8,000 ft. at Fort Smith on the afternoon of the 23d and were cirriform or unlimited in the morning hours at both places. Nevertheless, there was apparently enough

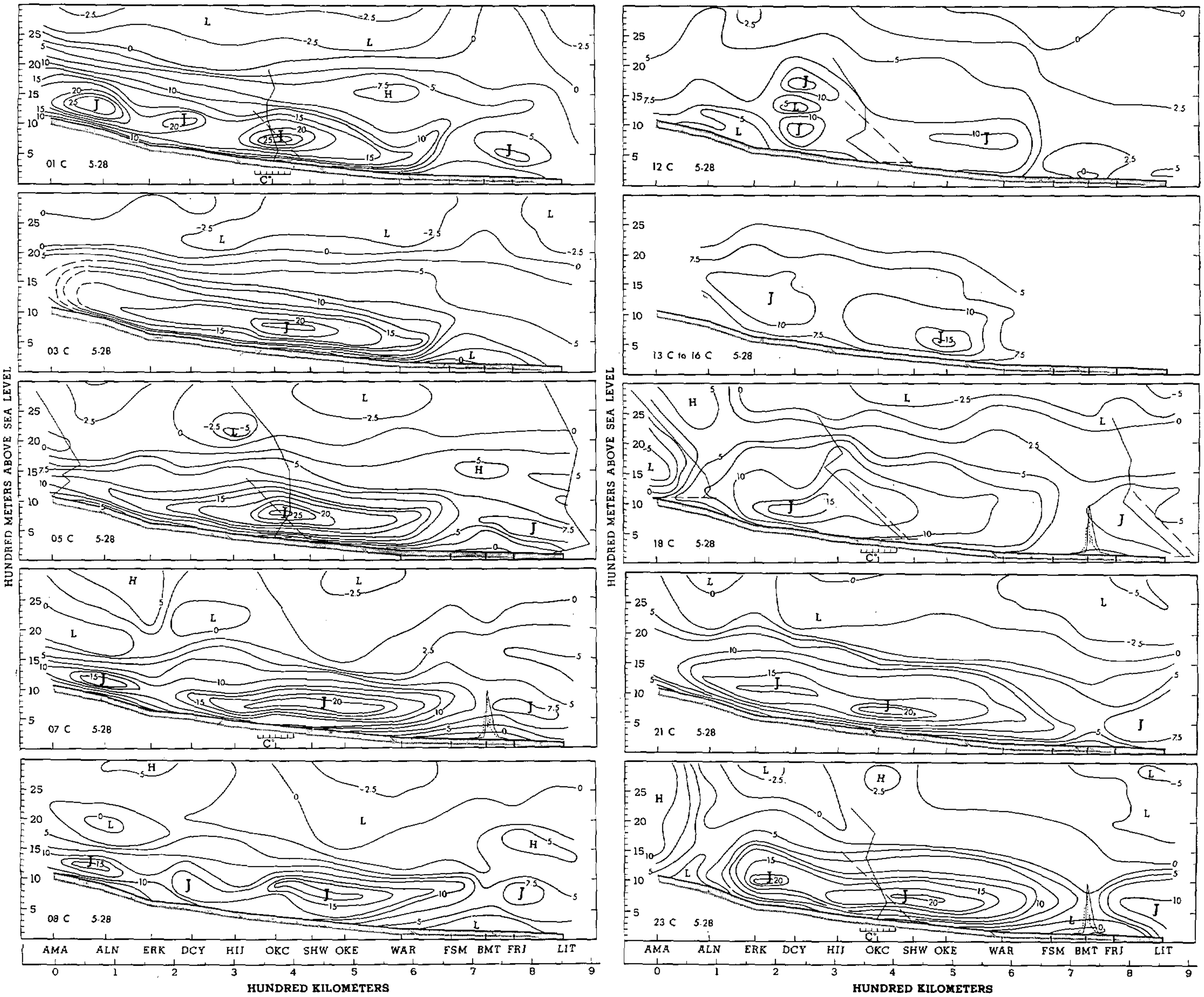

FIGURE 5.—Sequence of nine isotach cross-sections of southerly-component wind for the case of May 28, 1961. Wind speed is in meters per second. Following the cross-section for 1200 CST is an isotach cross-section averaged from 1300 to 1600 CST inclusive.

reduction of insolation to suppress the turbulent stress below that needed to break up the jet.

THE CASE STUDY OF MAY 28, 1961

The second observational period was from 0000 CST May 28 to 0000 CST May 29, 1961. This, fortunately, provided continuity over the daylight hours showing not only the degrading of the jet system that had been set up during the night, but the apparent continuing effort to reorganize the jet during the period of insolation. Eventually the jet was reestablished early in the evening.

This period was characterized by steep lapse rates (usually slightly super-adiabatic) at 1200 and 1800 CST, and ground based inversions at 0000 and 0600 CST in contrast to the persistent lapse conditions for the April case. Relying on the work of DeMarrais and Islitzer [4], one can confidently assume that the inversions began forming at the ground very close to sunset and worked upward during the night and that the surface inversions were broken from the ground upward after sunrise by a gradually thickening lapse layer.

The synoptic condition producing the jet for this period is represented by figure 4 where the sea level isobars are shown for 0600 and 1800 CST. The high pressure cell associated with the jet was not an extension of the Bermuda High, but rather a polar High located in Tennessee at the start of the period. Hence air entering the cross-section line was not from the Caribbean Sea but from farther north. The sea level pressure gradient for this period averaged ¾ of that for the April period, yet the jet system was much better organized and coherent and the maximum speeds reached were nearly as high. Only occasionally scattered clouds occurred over the line on May 28 as compared to long periods of broken to overcast skies for the April observation. Insolation and nocturnal radiation undoubtedly proceeded without hinderance. The radiative contrast is shown by the diurnal temperature range at Oklahoma City which was 28° F. on May 28 against about 13° F. on April 22–23.

As the observational period opened (0000 CST May 28), a well developed low-level southerly jet system consisting of three isotach maxima was in existence from Amarillo to Warner. The maximum development (greatest lateral extent and greatest core speed) of the jet system for the period occurred an hour later at 0100 CST, which is the first cross-section shown in figure 5. The highest observed wind speed, 25.4 m./sec., was found over Alanreed.[1] Note the consolidation of the jet into a single core of maximum speed at 0300 CST that continued on past 0600 CST. There was a partial return to the multi-cell structure at 0700 CST although the central cell dominated the system. Surface inversions were extant at all three raob stations at 0600 CST (shown on the 0500 CST cross-section), and the jet maximum at 0500 CST near Oklahoma City was centered on the top of the inversion there. However, at 0100 CST the jet was almost entirely in the lapse region above the surface inversion.

The regular, elegant structure of the jet system, evident since 0300 CST, began to break down and at 0800 CST was considerably weakened in maximum speed and coherence. At 1200 CST only a weak semblance of a jet existed westward from Warner to near Shawnee. Further, the entire afternoon, although not shown in figure 5, was characterized by the appearance of what can be called "jetlets" which were in evidence for one observation only and were not found in that same location for the observation before or afterward. Yet the impression persisted that on the average the jet system was continuously on the threshold of forming over the region between Erick and Warner. To test this idea the wind speeds were time-averaged for the period 1300 through 1600 CST for that part of the cross-section from Alanreed to Warner and a plot of the averaged speeds (shown as the cross-section following 1200 CST) was made. It reveals that a weak two-core jet system existed, on the average, supporting the contention that the low-level jet did not completely disappear during the warmest hours of the day.

By 1800 CST, a weak jet system was extant from near Alanreed to Fort Smith even though adiabatic lapses were observed at Little Rock and Oklahoma City. This jet persisted until the end of the period and reached a stable maximum speed of about 21 m./sec. by 2100 CST. Its speed maximum was above the top of the surface inversion at 2300 CST.

[1] Greatest observed speed for April 22–23 was 26 m./sec.

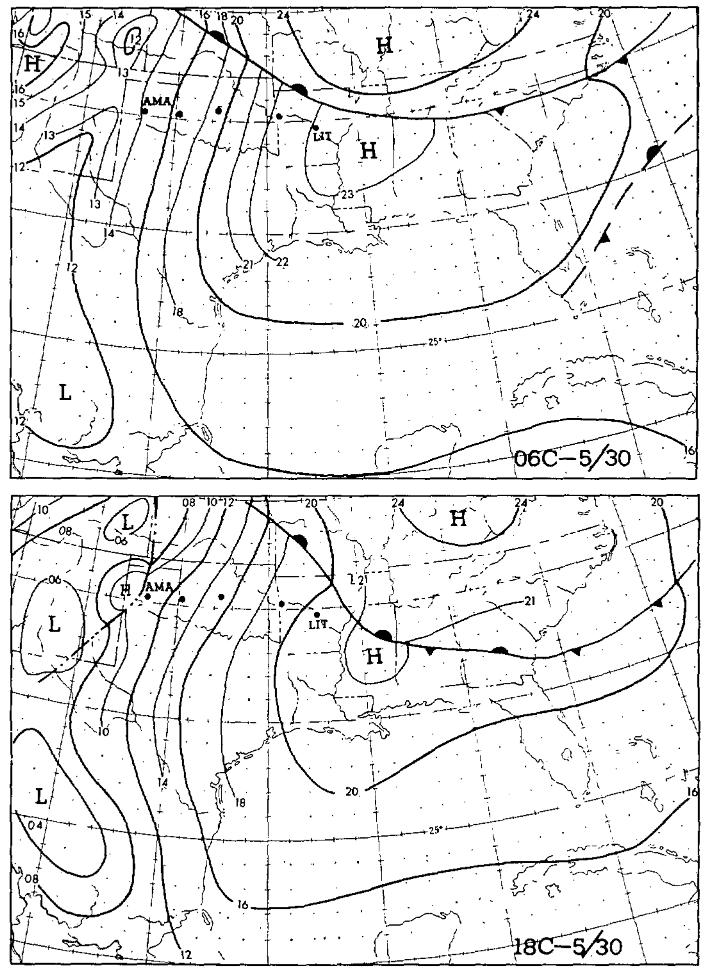

FIGURE 6.—Sea level synoptic maps for 0600 and 1800 CST, May 30, 1961.

Because of missing data at 0000 CST on the 29th, the maximum jet wind was not determined in the Oklahoma City to Okemah area, but the 2300 CST maximum real total wind was about 195 percent of the sea level geostrophic total wind. Two factors were most likely responsible for this large "over-shooting": (a) the existence of surface inversions that decreased surface friction, and (b) the decrease of the geostrophic wind from its 1800 CST value.

THE CASE STUDY FOR MAY 30, 1961

The synoptic picture for the observational period of 0000 CST May 30 to 0000 CST May 31 is represented by figure 6 showing the sea level isobaric pattern at 0600 and 1800 CST. A squall line backed by a meso-High system was advancing on Amarillo at 1800 CST.

Figure 7 shows that a well organized jet system existed at the beginning of the period (0000 CST). The height of its speed maximum was nearly constant at 400 m. above the sloping terrain and coincided with the top of the

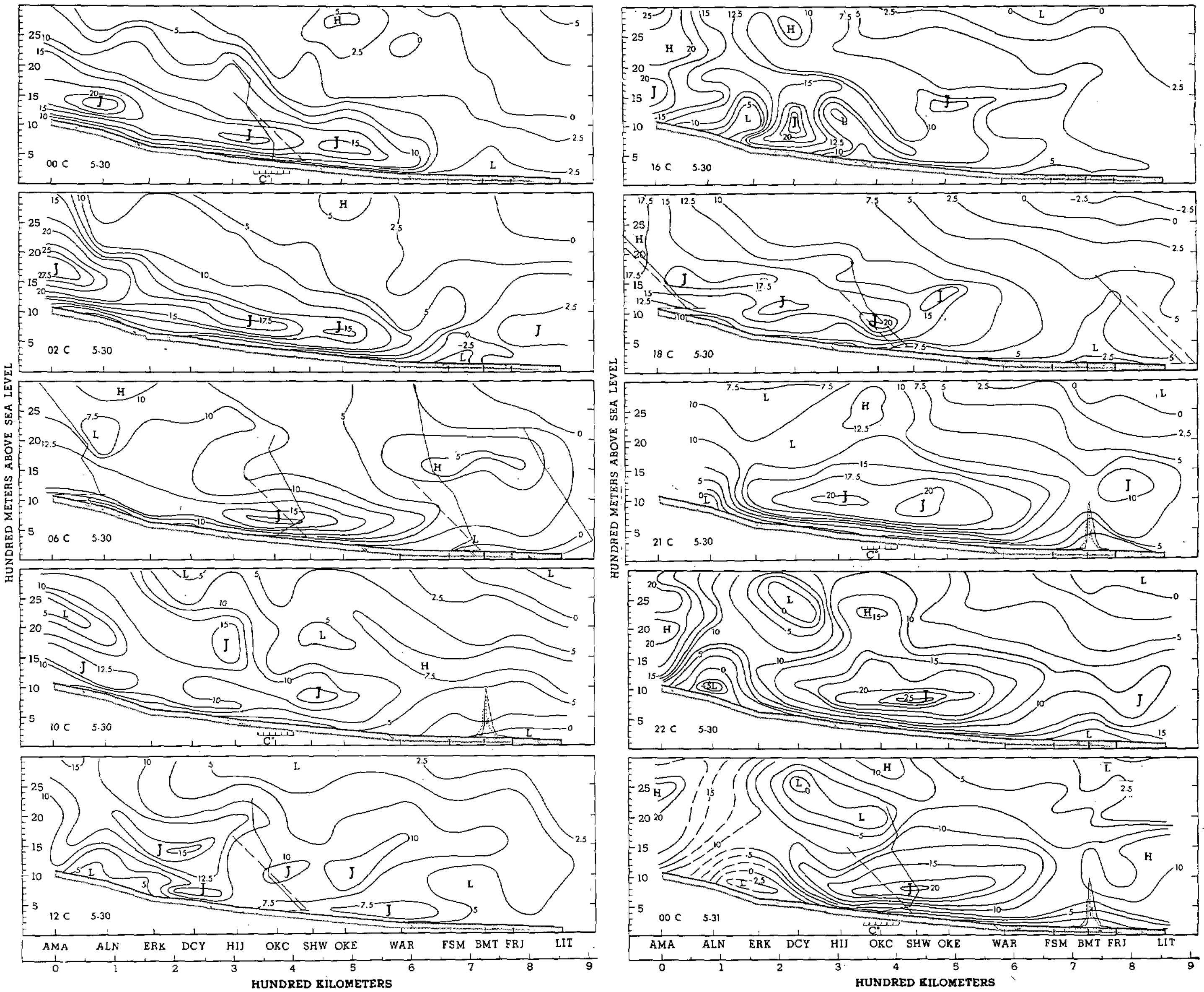

Figure 7.—Sequence of 10 isotach cross-sections of southerly-component wind for the case of May 30, 1961. Wind speed is in meters per second.

isothermal layer at Oklahoma City. The jet system continued on through 0600 cst when strong surface inversions were recorded at all raob stations except Amarillo. It is interesting that the jet speed maximum located near Oklahoma City at 0600 cst was below the top of the surface inversion. During the early morning hours the wind shadow region near Blue Mountain sustained light northerly-component flow.

From 1000 to 1700 cst temporary jetlets appeared in the flow causing general disorganization. The nearly adiabatic lapse rate in the lowest 700 m. at Oklahoma City at 1200 cst indicates the lack of stability over the area. The greatest degree of disorganization came at 1600 cst, about 1 hour after the time of maximum surface temperature, a period usually considered as the most unstable of the day in the low atmospheric levels.

At 1800 cst, the beginning of a jet system was evident even though adiabatic or greater lapse rates were extant from Amarillo to Little Rock. The jet increased in size and coherence until 2100 cst. At that time a thunderstorm prevented the observation at Amarillo and the intrusion of the associated meso-High is shown as a region of north-component speed over Alanreed at 2100 and 2200 cst and over Erick at 0000 cst on the 31st. It is also reflected to the west of Amarillo as a squall line on the 1800 cst sea level map. In the Hinton Junction to Shawnee area the maximum real total wind at 0000 cst on the 31st was 187 percent of the sea level geostrophic total wind at the same time and place.

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4. THEORETICAL CONSIDERATIONS

One of the prominent theories for the formation of the low-level jet, such as was shown in figures 3, 5, and 7 was proposed by Blackadar [2]. He has shown that the boundary-layer wind, which includes the jet, undergoes a diurnal oscillation similar to the theoretical inertial oscillation (cf. [11]). This oscillation is imposed on the existing wind beginning at the time of release of surface friction or at about 1800 LST. The maximum boundary-layer wind speed during the night is related to the magnitude of the ageostrophic vector ($\mathbf{V}'$ in fig. 8) at the time of release of friction. A schematic representation of the reaction showing the increase of the real wind from $\mathbf{V}_1$ to $\mathbf{V}_2$ is shown in figure 8. If the geostrophic wind remains constant during the period of interest, the real wind is accelerated by a rotating vector ($\dot{\mathbf{V}}$ in fig. 8) of constant magnitude which is perpendicular to the departure (ageostrophic) vector and rotates completely in one-half pendulum day. For the three cases examined here, the inertially accelerated wind speed was computed and compared in table 2 with the maximum real wind speeds in table 2 at or near identical times. To help eliminate the effect of the changing geostrophic wind, the average of the geostrophic wind at 1800 CST and 6 hours later was used in the computation. Since the geostrophic wind had been determined in the area around Oklahoma City (Hinton Junction to Okemah) the real wind speed shown in the table is the average of the maximum jet wind observations in the same area. Here total winds were used instead of the southerly components used in the cross-sections.

Observed maximum real wind speeds for the two May cases at or near 0000 CST (on the following calendar day) in the Oklahoma City area were considerably super-geostrophic, but the table also shows that the geostrophic wind decreased in the 6 hours prior to that time. The observed maximum real wind speed at 0000 CST on April 23 was only slightly super-geostrophic, partly because the geostrophic wind increased in the previous 6 hours. The maximum real wind speeds for 0000 CST April 23 and 2300 CST May 28 were almost identical to the computed inertially accelerated wind for the same time, but for May 30 the real wind (at 0000 CST, 31st) was somewhat less that the computed wind. An exception existed on May 30 at 2200 CST when the real wind (25 m./sec.) was a little greater than the computed wind. So in all three cases the inertial theory could account for the total increase in magnitude of the boundary-layer wind. However, vector

TABLE 2.—*Comparison of real, geostrophic, and inertially accelerated winds. Wind speeds are in meters per second*

Case study of—	Time CST	April 22/23	May 28	May 30
Real wind	0000	24.6 (23d)	21.3 (2300 CST 28th).	18.3 (31st) (25 at 2200 CST).
Inertially accelerated wind	0000	24.9 (23d)	21.6 (29th)	23.5 (31st)
Geostrophic wind	1800	15 (22d)	17 (28th)	18 (30th)
Geostrophic wind	0000	21 (23d)	11 (29th)	10 (31st)

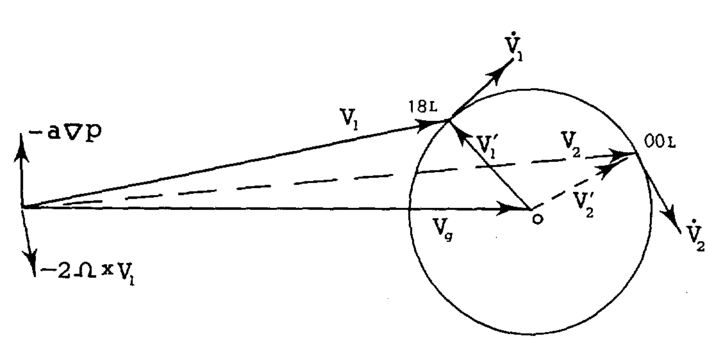

FIGURE 8.—Schematic representation of the inertial oscillation and the manner in which it modifies the 1800 LST wind during the nighttime hours. Here $\mathbf{V}'=\mathbf{V}-\mathbf{V}_g$.

differences of 6 to 8 m./sec. existed. Many more measurements would be required to make any firm statements, partly because of the possible inaccuracies in measurement of the upper wind and variations of the geostrophic wind. However, knowing the real and geostrophic wind vectors at about 1800 CST, and having a forecast of the geostrophic wind for midnight or later, a forecaster, for example, could estimate the maximum low-level wind to be expected at various times during the night, and within some few meters per second. The location of the maximum would be another matter, but the height, according to the theory, would be just at the top of the surface inversion. A cloudless night (to insure formation of an inversion) with a fair sea level pressure gradient would also be required.

Another prominent theoretical treatment, that proposed by Wexler [13] involves the turning northward along the Central American mountains of tradewind air that enters the Gulf of Mexico and the Caribbean Sea as shown schematically in figure 9. The theory involves a two-layer model, the upper layer stationary, the lower flowing northward below 2 km. This air that is turned northward furnishes the volume used by the high-speed jet system. The principle of the jet is explained qualitatively by the conservation of absolute vorticity. If $(f+\zeta)/D$ is constant for air columns moving northward and if D, column thickness, remains constant, then as f, the Coriolis parameter, increases with increasing latitude the columns of air must take on increasing anticyclonic vorticity, ζ, relative to the earth. If this is converted mainly into anticyclonic shear, then a high-speed current must develop on the western boundary of the flow regardless of the time of day. Lateral friction with the high plains and Rocky Mountains causes strong shears of the opposite sense on the western side of the boundary-layer flow giving the appearance of a true jet in the horizontal. Friction with the ground would cause vertical wind shear in the surface layer. Above the surface layer, where the boundary layer acceleration does not take place, the speed (still speaking of the theoretical model) is zero (north-south direction) so that the flow also has the appearance of a jet in the vertical. The speed profile of the jet would change greatly from afternoon to early morning, and even disappear tem-

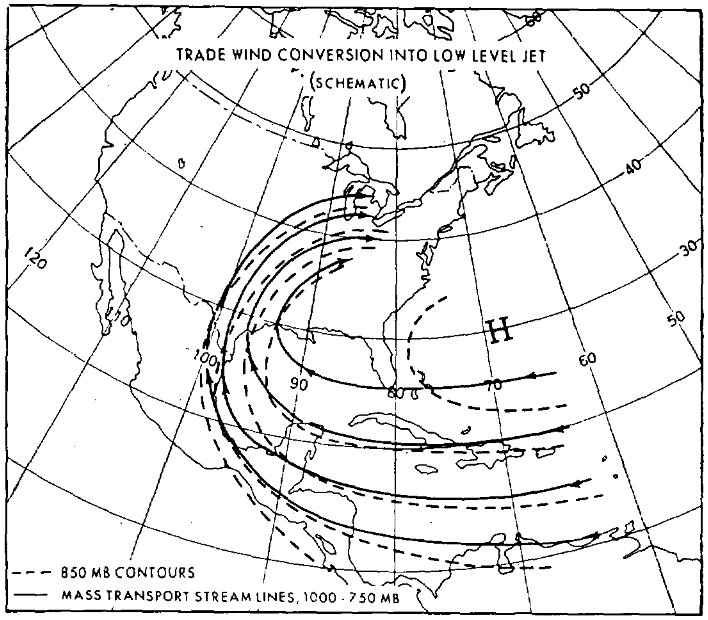

Figure 9.—Schematic plan of trade-wind air entering the Caribbean Sea, Gulf of Mexico, and the southern United States. (After Wexler [13])

porarily during the hot hours of the day, with strong diurnal variation of vertical friction stress acting on the current.

Although Blackadar allows for the occurrence of a "jet-like" wind profile during the daytime when a rapid decrease of geostrophic wind with height exists, Wexler's theory requires that the jet exist at all hours of the day, as long as the low-level flow from low latitudes exists, although considerably retarded (by surface friction) during the period of insolation. The existence of an average jet from 1300 to 1600 CST on May 28 and the persistence of the jet during daylight hours on April 23 adds support to the contention here that Wexler's theory more nearly explains the mechanism of the jet system. However, it is not out of the realm of possibility that both mechanisms operate simultaneously, and sometimes additively. It should be pointed out that whereas Wexler's theory requires a current from low latitudes with a predominantly southerly component for the generation of the low-level jet, Blackadar's theory does not, although a certain amount of the latter's work was done with summer-season southerly-component winds.

5. CONCLUDING REMARKS

In a review of the cited literature on the "low-level jet" it is found that there are about as many concepts of the jet as there are writers on the subject. Some of the concepts are rather loose and include any relatively strong wind current, usually with a southerly component, from the 850-mb. surface downward. Other concepts, such as those of Blackadar and Wexler are rather restrictive and involve sophisticated diurnal reaction of the boundary-layer wind with the Coriolis parameter and frictional coupling with the ground. Most of the findings of this investigation are descriptive and need little amplification. However, they appear to fit in, to a greater or lesser degree, with both of the theories mentioned above.

Each of the three cases was different in detail, yet the synoptic pattern in the pibal line area was essentially the same in each case. It would seem that variations in frictional coupling with the ground caused by variations in daytime cloudiness and nighttime surface thermal changes constituted the major modifying factors. This is particularly noticeable between the April case, when the jet existed all day, and the other two when it degraded considerably during daylight hours. But the source air for the April case came from lower latitudes and this may have accentuated the southerly current in line with Wexler's theory.[2] Yet the most orderly nocturnal jet systems, those of May 28 and 29, came from air of polar Highs and the source was therefore farther north than the April case, implying that a lesser amount of anticyclonic shearing effect was being applied.

The low-level jet systems, as observed in 1961, seem to refute both theories at times. In particular, the behavior of the jet of April 22–23 is contrary to Blackadar's theory, since it existed at night when no surface inversion was present and also during the day when, even though an inversion was present above the surface, the jet was below it in lapse conditions extending to the surface. The jet systems of May 28 and 30, forming from polar air sources, indicate that trade-wind-source air is not necessary for southerly low-level jet activity, this time contrary to the proposal of Wexler.

It would seem to the author that the boundary-layer jet with its maximum wind in the 300- to 700-m. level would be the most troublesome to aviation interests and to forecasters, yet, its narrow vertical dimension and relatively short period of existence usually prevent its detection with the present upper-air observing system. Reliable methods for its prediction need to be developed or the observational system should be modified to detect it adequately.

For the purpose of clarification, the author would like to see the term, "low-level jet" applied only to boundary-layer winds such as conceived by Blackadar and Wexler and as described in this paper, and not to include horizontal wind maxima in the 850-mb. level which may only be a reflection of higher-level tropospheric wind maxima.

6. FUTURE OBSERVATIONS

The single observational line used in 1961 for detecting the southerly low-level jet, although the most definitive of its kind ever to be used, left several things to be desired. Among these were the lack of measured surface winds, the coarseness of the data points in the vertical, and the inability to determine advective changes in the jet systems. Any future similar research observational

[2] The reader is reminded that the anticyclonic shearing effect is most effective in lower latitudes because of the greater latitudinal variation of the Coriolis parameter there.

projects should include: (a) two east-west lines of pibal stations so spaced in the north–south direction as to determine the advection changes; (b) surface wind speed and direction measuring equipment; (c) if possible, one-half minute readings of the balloon (consideration of a slower-rising balloon should be made); (d) closely-spaced-in-time raob observations to determine the onset and breakup of surface inversions; and (e) the use of tetroons for determining the vertical and horizontal air motions through the two proposed cross-section lines such as have been used by Angell and Pack [1] and Pack [10]. Under (d) above, consideration should be given to the use of the inexpensive T-sonde as described by Dickson [5].

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REFERENCES

1. J. K. Angell and D. H. Pack, "Estimation of Vertical Air Motions in Desert Terrain from Tetroon Flights," *Monthly Weather Review*, vol. 89, No. 8, Aug. 1961, pp. 273–283.
2. 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.
3. J. G. Charney, "The Gulf Stream as an Inertial Boundary Layer," *Proceedings of the National Academy of Sciences*, vol. 41, 1955, pp. 731–740.
4. C. A. DeMarrais and N. F. Islitzer, "Diffusion Climatology of the National Reactor Testing Station," U.S. Weather Bureau-U.S. Atomic Energy Commission, Idaho Falls, Idaho, April 1960, IDO–12015, pp. 33–43.
5. C. R. Dickson, "Description and Operation of the T-Sonde," *Monthly Weather Review*, vol. 91, No. 1, Jan. 1963, pp. 33–36.
6. T. Durosko, "Low-Level Jet Stream," *Flying*, vol. 71, No. 4, Oct. 1962.
7. 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, April 1954, pp. 166–170.
8. G. W. Morgan, "On the Wind-Driven Ocean Circulation," *Tellus*, vol. 8, No. 3, Aug. 1956, pp. 301–320.
9. C. W. Newton, "Synoptic Comparisons of Jet Stream and Gulf Stream Systems," University of Chicago, Department of Meteorology, *Technical Report No. 1 to ONR*, Feb. 1959, 34 pages (also in *The Atmosphere and the Sea in Motion*, The Rossby Memorial Volume, The Rockefeller Institute Press with Oxford University Press, New York, 1960, pp. 288–304).
10. D. H. Pack, "Air Trajectories and Turbulence Statistics from Weather Radar Using Tetroons and Radar Transponders," *Monthly Weather Review*, vol. 90, No. 12, Dec. 1962, pp. 491–506.
11. S. Petterssen, *Weather Analysis and Forecasting*, "Motion and Motion Systems," McGraw-Hill Book Co., New York, 1956, 428 pp. (see pp. 60–61).
12. R. K. Polson, "Sunrise Wind—How to Find and Use It," *Business and Commercial Aviation*, Feb. 1958, pp. 42–44.
13. H. Wexler, "A Boundary Layer Interpretation of the Low-Level Jet," *Tellus*, vol. 13, No. 3, Aug. 1961, pp. 369–378.