NOTES AND CORRESPONDENCE

On the Role of Upper Tropospheric Jet Streaks and Leeside Cyclogenesis in the Development of Low-Level Jets in the Great Plains

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ABSTRACT

A review of 15 cases of low-level jets (LLJ's) which developed in the Great Plains and which have been previously discussed in the literature is presented. The review notes that boundary-layer processes have been emphasized as causative factors in the development of the LLJ while upper tropospheric features were not considered and the importance of synoptic-scale processes was generally minimized. For 12 out of the 15 cases, a systematic upper level flow pattern is isolated which includes the existence of a trough over the southwest United States and the propagation of upper level jet streaks from the Rocky Mountains toward the Great Plains. This flow pattern is responsible for leeside cyclogenesis or leeside troughing that produces the pressure gradients needed for the development of LLJ's. For the other three cases, a blocking ridge exists over the Great Plains and the upper level flow is relatively weak. It is during these situations that the "classic," diurnally oscillating LLJ is observed. A more detailed review of four case studies indicates that the subsynoptic-scale processes associated with the upper level jet streak's forcing of leeside cyclogenesis could, at times, be an important factor in the development of LLJ's in the Great Plains. The review questions 1) the notion that a retrogression of the subtropical high provides the increased pressure gradient force needed for the development of a LLJ in the Great Plains region, and 2) the assumption of using a constant or diurnally oscillating pressure gradient force which has been used for studying the total evolution of the LLJ. Changes in the pressure gradient force related to leeside cyclogenesis and leeside troughing and the isallobaric wind response to these changes seem to be an integral part of the process that leads to the development of LLJ's observed in the Great Plains.

1. Introduction

The interaction between upper and lower tropospheric jet streaks is widely recognized as an important factor in the development of organized convective storm systems (e.g., Petterssen, 1956b; Newton, 1967). The tendency has been to treat low-level jets (LLJ's) and upper tropospheric jet streaks as separate entities. However, Reiter (1969) and Uccellini and Johnson (1979) present evidence which indicates that, in some cases, upper and lower tropospheric jets are a coupled entity. Results from the Uccellini and Johnson case study show that 1) a LLJ beneath the exit region of an upper tropospheric jet streak is embedded in the lower branch of an indirect circulation, 2) the development of the LLJ is largely due to an increased lower tropospheric isallobaric wind component, and 3) the development of the LLJ is coupled to the upper tropospheric jet streak by mass adjustments within the exit region of the streak. The Uccellini and Johnson case study illustrates the importance of subsynoptic-scale mass adjustments in forcing the development of a LLJ and producing the differential moisture and temperature advections that convectively destabilize the atmosphere and lead to the development of severe convective storms.

The purpose of this note is to explore the problem of applying the concept of coupled jet streaks to the large number of LLJ's which occur in the Great Plains. In Section 2, a literature review is presented which notes that boundary-layer processes and terrain effects have been emphasized as causative factors in the development of low-level jets in the Great Plains, while upper tropospheric characteristics and processes were not considered. In Section 3, 15 LLJ cases in the Great Plains that have been previously discussed in the literature are reviewed to see if any systematic synoptic forcing is common to these cases. A summary of the results is presented in Section 4.

2. Low-level jets in the Great Plains

Bonner's (1968) statistical analysis confirms that a large number of LLJ's occur in the Great Plains, with the maximum number existing from Texas to Nebraska and a secondary maximum located along

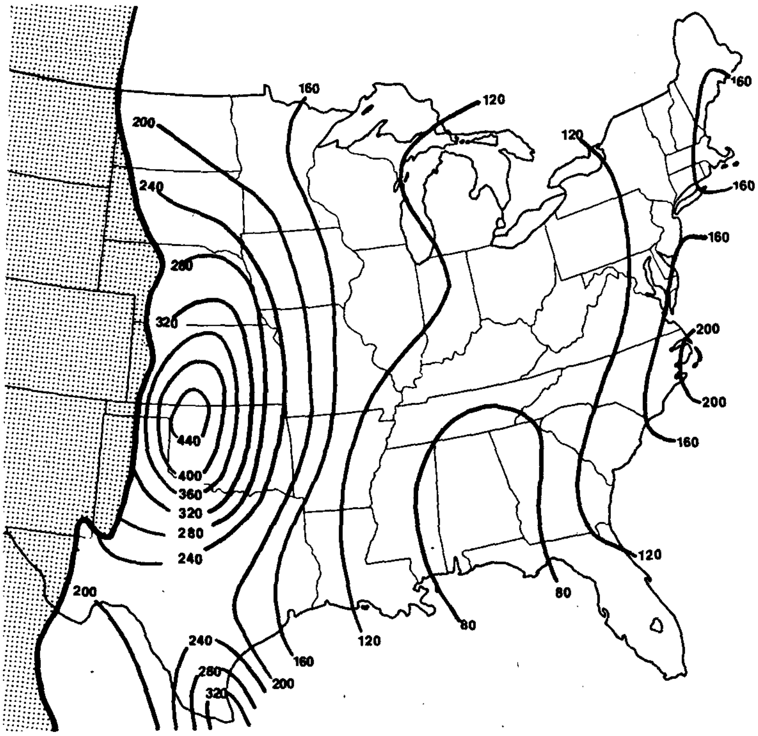

FIG. 1. Number of low-level jet observations from January 1959–December 1960 at 1200 and 0000 GMT (from Bonner, 1965).

the North Carolina coast (Fig. 1). Means (1952, 1954) and Bonner (1966) show that the low-level jets in the Great Plains are especially important for their rapid transport of heat and moisture from the Gulf region into areas of convective storms which produce heavy rainfall. The LLJ's in the Great Plains region are characterized by a diurnal oscillation, as the wind speeds reach maximum intensity by early morning, and are associated with the development of a nocturnal temperature inversion (Blackadar, 1957; Wexler, 1961; Hoecker, 1963; Izumi and Barad, 1963; Izumi, 1964; Lettau, 1967; Bonner, 1968). The westward extension of the North Atlantic subtropical high (Wexler, 1961), boundary-layer mixing processes (Blackadar, 1957) and the diurnal radiation cycle over sloped terrain (Lettau, 1967), with greater emphasis placed on the topographical characteristics by Paegle and Rasch (1973) and Paegle (1978), have all been related to the generation of the LLJ and its seasonal, temporal and geographic preference.

Reiter (1969), Newton (1956, 1967) and Naistat and Young (1973) all present evidence that low-level jets[1] may also develop in response to synoptic- or subsynoptic-scale processes particularly through a response to leeside cyclogenesis common to the Great Plains. For the large number of jet cases collected for a climatological summary, Bonner (1963) stated "On roughly 60% of the jet days at each station, cold fronts or low pressure centers were to be found within 350 n mi to the west of the station. On roughly one half of *these* days, frontal passage occurred within the next twelve hours." In a recent discussion, Bonner[2] noted that the organized, coherent LLJ's in the Great Plains which could be analyzed within a region (rather than being obvious at only a few widely separated stations) are frequently associated with leeside troughing, leeside cyclogenesis or a frontal passage associated with a cyclone located further to the north. These observations serve as a motivation for reviewing cases of LLJ's previously reported in the literature for which boundary-layer processes and terrain

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[1] In an attempt to better define lower tropospheric wind fields, Reiter (1969) refers to the diurnally oscillating LLJ as an "Inversion Wind Maximum" which is restricted to a planetary boundary layer (PBL) depth of 400–500 m. Reiter contrasted this type of PBL wind maximum to low-level jets which seem to be related to synoptic-scale forcing and can extend beyond the PBL up to the 700 mb level. In selecting the cases for this review, no attempt was made to classify the LLJ cases along the lines proposed by Reiter. However, given the results in Section 3, it seems that such a distinction may be needed to define different types of low-level jets for which different forcing mechanisms might be important, especially for the Great Plains region.

[2] Personal communication.

effects were emphasized and upper tropospheric and other synoptic features were not considered.

3. Review of low-level jet case studies

An extensive research effort was undertaken in the 1960's with special pilot balloon (PIBAL) networks and tower measurements to study the forcing of low-level jets and to test the theories concerning the LLJ previously presented by Blackadar (1957) and Wexler (1961). Table 1 lists 15 cases of LLJ's which were used in these studies and include four cases from 1961 (Hoecker, 1963; Bonner, 1963, 1966) for which special network data are available. The cases listed in Table 1 include all seasons and situations with and without convective storms. Newton's (1956) study of leeside cyclogenesis is listed in Table 1 since it also includes a description of a strong LLJ in the Great Plains. Except for the Newton paper, none of the case studies in Table 1 include any meteorological charts or other information above the 700 mb level.

As a first step in reviewing the previously documented cases of the LLJ, upper air maps were collected for each case, reviewed and categorized as several basic flow patterns became readily apparent. The schematic in Fig. 2 summarizes the upper tropospheric flow which prevails during the occurrence of a LLJ and shows that two basic patterns exists for these cases. The first type consists of a trough over the Rockies and ridge located in the eastern third of the country with significant upper tropospheric jet streaks propagating toward the Great Plains from the Nevada–California region (polar origin) and from the Arizona–Mexico region (subtropical origin). These conditions existed for 12 out of the 15 cases. There is considerable variability in the magnitude of the trough and upper tropospheric jet streaks located over the western United States for those 12 LLJ cases. However, the existence of a 300 mb trough over the far west, upper tropospheric jet streaks propagating toward the Great Plains, and the development of a leeside cyclone or trough that occurs with this type of upper tropospheric flow (Newton, 1956; Hovenac and Horn, 1975) is quite consistent. The second pattern, which existed for 3 out of 15 cases, consists of a strong ridge located over the front range of the Rockies with weak upper tropospheric flow over the north Texas, western Oklahoma–Kansas

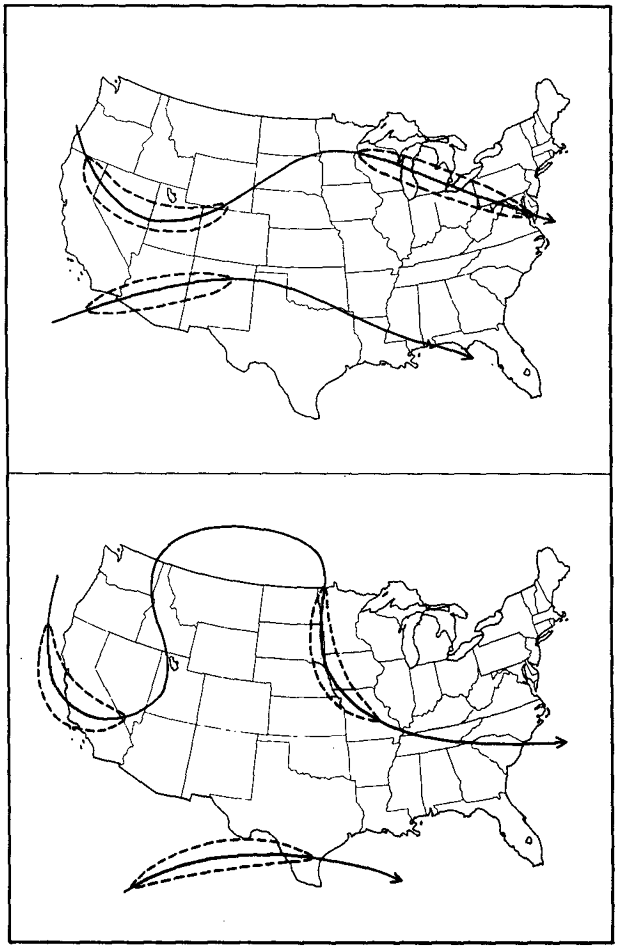

FIG. 2. Schematic of upper tropospheric (300 mb) flow patterns for 15 cases of low-level jets in the Great Plains. Top: type 1 condition for 12 out of the 15 cases. Bottom: type 2 condition for the other three cases. Shaded areas represent positions of upper level jet streaks.

TABLE 1. Cases of low-level jets used in literature review.

Date	Author	Type
14 July 1959*	Bonner (1965)	2
14 August 1959*	"	1
20 August 1959*	"	1
19 April 1960	"	1
22 April 1960	"	1
23 April 1960	"	1
10 July 1960	"	1
23 August 1960	"	1
2 December 1960	"	1
15 March 1961	Izumi (1964)	2
23 April 1961	Hoecker (1963)	1
28–29 May 1961	"	2
30 May 1961	"	1
16–17 May 1961	Bonner (1963, 1966)	1
17–19 November 1948**	Newton (1956)	1

Type 1: Trough upstream and ridge downstream of southern Great Plains with 300 mb jet streak propagating into region.

Type 2: Ridge located directly over Great Plains with weak upper tropospheric winds.

* 250 mb charts reviewed for upper level analysis.

** Actual winds on 300 mb charts not available.

region. The well-documented LLJ cases which clearly display the diurnal wind oscillation with a nocturnal maximum coinciding with a boundary-layer inversion (e.g., Izumi, 1964; Hoecker, 1963) are associated with this type of flow.

The three Hoecker cases (Table 1) illustrate the variable nature of the LLJ's observed in the southern Great Plains during the special observation period in 1961 and also provide evidence on the relative influence that boundary-layer processes have on the LLJ as a function of the synoptic-scale forcing. The 28–29 May 1961 case of a LLJ in the southern Great Plains illustrates the "classic" diurnal oscillation in the magnitude and coherency of the LLJ (see Fig. 5 in the Hoecker paper). The LLJ, which remained just above the boundary layer temperature inversion (400 m), reached a maximum value of 25 m s^{-1} between 0600–1200 GMT, weakened immediately after sunrise to a 15 m s^{-1} maximum and increased again after sunset. The LLJ appeared to be well organized during the night but was less coherent during the day, apparently as a result of the solar insolation and increased boundary layer turbulence. The surface maps for 28 May display a relatively weak pressure gradient in the southern Great Plains associated with a weakening inverted trough in Oklahoma (Fig. 3). The 300 mb flow was also weak in the southern Great Plains with the height contours illustrating a type-2 condition defined in Table 1.

The 30–31 May 1961 case from Hoecker provides additional evidence of a diurnal oscillation but also shows a deviation from the classic pattern. During the early morning of 30 May, the LLJ increased to 20 m s^{-1} over Oklahoma and remained at the 400 m level coinciding with the inversion level (see Fig. 7 in the Hoecker paper). Immediately after sunrise, the LLJ appeared to break down into several maxima and thus became less coherent. However, the magnitude of maximum velocity only decreased from the previously reported 20 m s^{-1} to 15 m s^{-1}. The LLJ began reorganizing and increasing in magnitude *during the afternoon* rather than after sunset and finally increased to 25 m s^{-1} by 2200 CST 30 May. The surface map for 30 May shows a developing pressure gradient associated with a leeside trough as the 300 mb trough shifted east from its 28 May position (Fig. 3). Relatively weak jet streaks propagated toward the southern Great Plains with the exit region of the subtropical jet coinciding with the positions of the leeside trough and the LLJ in the Oklahoma region.

The 23 April 1961 case from Hoecker is characterized by much larger synoptic-scale forcing than the previous two cases as a major leeside cyclone developed within the exit region of a jet streak propagating toward the Great Plains from the Pacific Coast (Fig. 3). The surface pressure gradient in this case was nearly a third larger than the other two cases. Although the 25 m s^{-1} magnitude of the LLJ observed in Oklahoma on 23 April (see Fig. 3 in Hoecker paper) was no larger than the magnitudes observed in the other cases, the persistence and general characteristics of the LLJ were noticeably different. The LLJ increased during the night of 22 April and morning of 23 April as the pressure gradient also increased in the Great Plains region in response to the leeside cyclogenesis. Unlike the other cases, the LLJ did not rapidly weaken during the morning but persisted and remained coherent well into the afternoon with the magnitude of the LLJ remaining >20 m s^{-1}. Although Hoecker attributes the behavior of the LLJ in the 23 April case to a westward extension of the subtropical high and daytime cloud cover it appears that the intense cyclogenesis, and the upper tropospheric jet streaks which are important for leeside development (Newton, 1956; Hovenac and Horn, 1975), are more likely responsible for the strong pressure gradient in the Great Plains and persistent nature of the LLJ for this case.

The 16–17 May 1961 case, previously analyzed by Bonner (1963, 1966) using the special PIBAL network, offers additional evidence that the combined effects of upper tropospheric jet streaks and leeside cyclogenesis can influence the behavior of LLJ's in the southern Great Plains. In this case, the LLJ was well established in southwest Kansas *in the afternoon* of 16 May and shifted southeastward to Oklahoma by early evening [0000 GMT 17 May (Fig. 4)]. During the night, the magnitude of the wind maximum increased to over 30 m s^{-1} as the position of the LLJ continued to shift eastward then northeastward to southwest Missouri by 1200 GMT 17 May.

Fig. 4 also includes the surface pressure tendencies computed over a 2 h interval by Bonner (1963) and smoothed to eliminate high-frequency perturbations related to individual thunderstorm cells. The heavy vectors which are superimposed on the streamline and pressure tendency field in Fig. 4 represent inertial and isallobaric approximations to the ageostrophic wind (Uccellini and Johnson, 1979) which could be important in the development of the LLJ. Bonner noted that at any time, the isallobaric ageostrophic wind tended to be perpendicular to the axis of the LLJ and that the geostrophic wind was a better approximation to the real wind. However, the isallobaric wind and the ageostrophic component related to the eastward shift of a confluence zone in the streamline analysis could continuously contribute to parcel accelerations into the observed locations of the LLJ and therefore play an important role in the evolution of the LLJ as depicted in Fig. 4. Between 1800 and 0000 GMT, the area of maximum pressure falls shifted southeastward from the Texas panhandle to north-central Texas and then by 0600 GMT northeastward to southeast Missouri. The position of the LLJ also shifts southeast by 0000 GMT 17

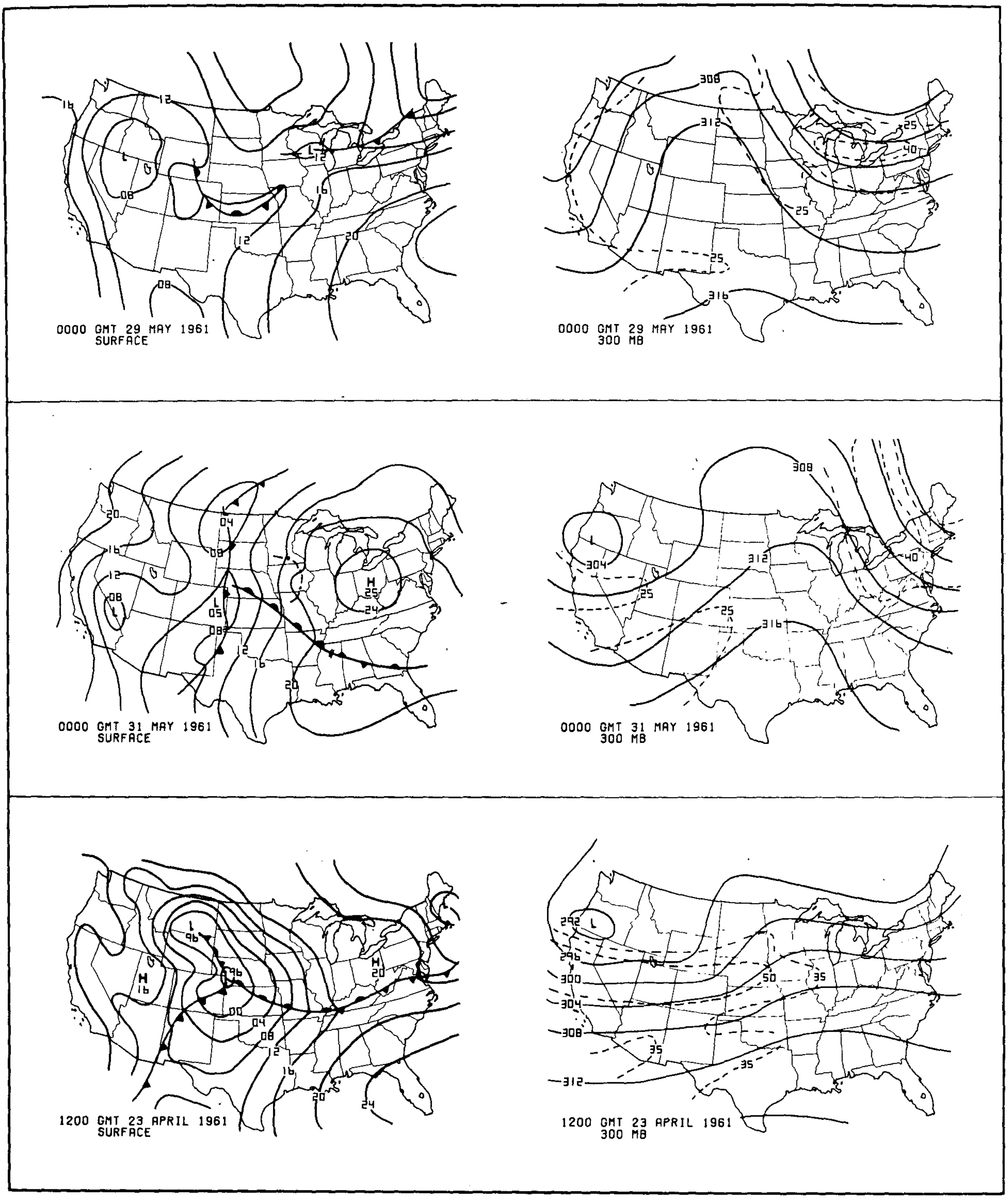

FIG. 3. National Weather Service surface and 300 mb analyses for three cases of low-level jets analyzed by Hoecker (1963). Top: 0000 GMT 29 May 1961; middle: 0000 GMT 31 May 1961; bottom: 1200 GMT 23 April 1961. Surface isobars in millibars (12 is 1012 mb); 300 mb heights in geopotential feet (308 is 30 800 gft); isotachs are meters per second^{-1}.

May, then east, then northeast by 1200 GMT 17 May, being consistently located within an area of maximum pressure falls analyzed 6 h earlier.

The relative positions of the confluence zone and the area of pressure falls upwind of the LLJ would both contribute to parcel accelerations in the along-stream direction into the core of the LLJ. For example, lower tropospheric parcels located in northeast and north Texas at 0000 GMT 17 May have an ageostrophic component directed to the

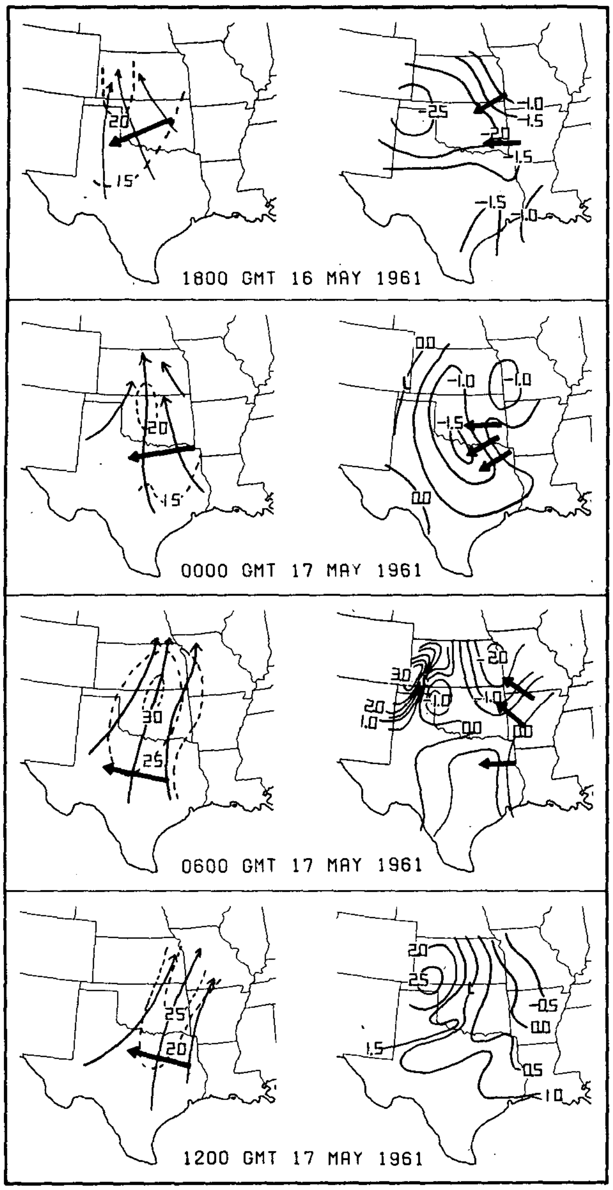

FIG. 4. Isotach (m s^{-1}) and streamline analyses at the 1 km level (left) and surface pressure tendencies [mb 2 h^{-1}] for the 16–17 May 1961 case study. Heavy lines represent an ageostrophic component related to confluent streamlines (left) and the isallobaric wind (right) both of which contribute to an alongstream acceleration for parcels entering the low-level jet (from Bonner, 1963).

west approximated by the confluent streamlines and isallobaric wind (Fig. 4). The ageostrophic component would, in turn, lead to parcel accelerations toward north central Oklahoma where the LLJ was located by 0600 GMT. Similarly, given the confluence zone in north Texas and the axis of negative pressure tendency from northeast Texas to northeast Kansas at 0600 GMT, parcels located in northeast Oklahoma down to Texas at 0600 GMT would undergo accelerations toward southwest Missouri where the LLJ was located at 1200 GMT 17 May (Fig. 4). The evolution of the lower tropospheric wind and height fields and surface pressure tendency pattern in this fashion is consistent with a mutual and continual mass-momentum adjustment occurring on a subsynoptic scale in association with the eastward movement of the low-pressure system.

The upper tropospheric features and synoptic-scale characteristics of the 16–17 May 1961 case are illustrated in Fig. 5. Between 0000 and 1200 GMT, two upper tropospheric jet streaks propagated eastward into the Great Plains region. Leeside cyclogenesis terminated by 0000 GMT 17 May as the surface low filled by 1200 GMT. The 850 and 300 mb maps in Fig. 5 and the isotach maps at 0000 GMT and 1200 GMT 17 May in Fig. 4 reveal that at both times the LLJ extended well beyond the PBL and was located in the exit region of the southernmost upper level jet streak. Combining the information from Figs. 4 and 5 suggests that the evolution of the LLJ and especially its eastward shift during the 12 h period (0000–1200 GMT 17 May) was linked to the upper level jet's propagation and associated mass adjustments as discussed by Uccellini and Johnson (1979). Of course, it would take a thorough analysis to confirm this interpretation and to determine the relative importance of these processes as compared to the boundary-layer processes which could also contribute to the increase in wind speed observed between 0000 and 0600 GMT (Fig. 4). However, it is quite evident that processes other than boundary-layer inertial oscillations and retrograding subtropical highs are influencing lower tropospheric winds in this case.

4. Summary and discussion

In this paper, 15 cases of LLJ's that were previously discussed in the literature are reviewed to determine if the coupling concept recently presented by Uccellini and Johnson (1979) has any relevance to the large number of LLJ's observed in the southern Great Plains. In 3 of the 15 cases, the upper troposphere over the Great Plains is characterized by a significant ridge and weak upper tropospheric flow (type 2). The cases of well-documented LLJ's restricted to the PBL and characterized by a diurnal oscillation are associated with this type of upper tropospheric pattern and with relatively weak surface pressure gradients. In 12 out of the 15 cases, the synoptic pattern is characterized by upper tropospheric jet streaks propagating toward the Great Plains from the Rocky Mountain area with the surface pressure gradients increased by leeside cyclogenesis or leeside troughing (type 1). In these cases, the LLJ's 1) tend to be located within the exit region of the upper level jet, 2) are directed toward the cyclonic side, and 3) deviate from the classic pattern in that the LLJ is well defined, coherent and more persistent even in the afternoon and extend beyond the PBL. However, there is still a tendency for the maximum winds to be observed in the early morning

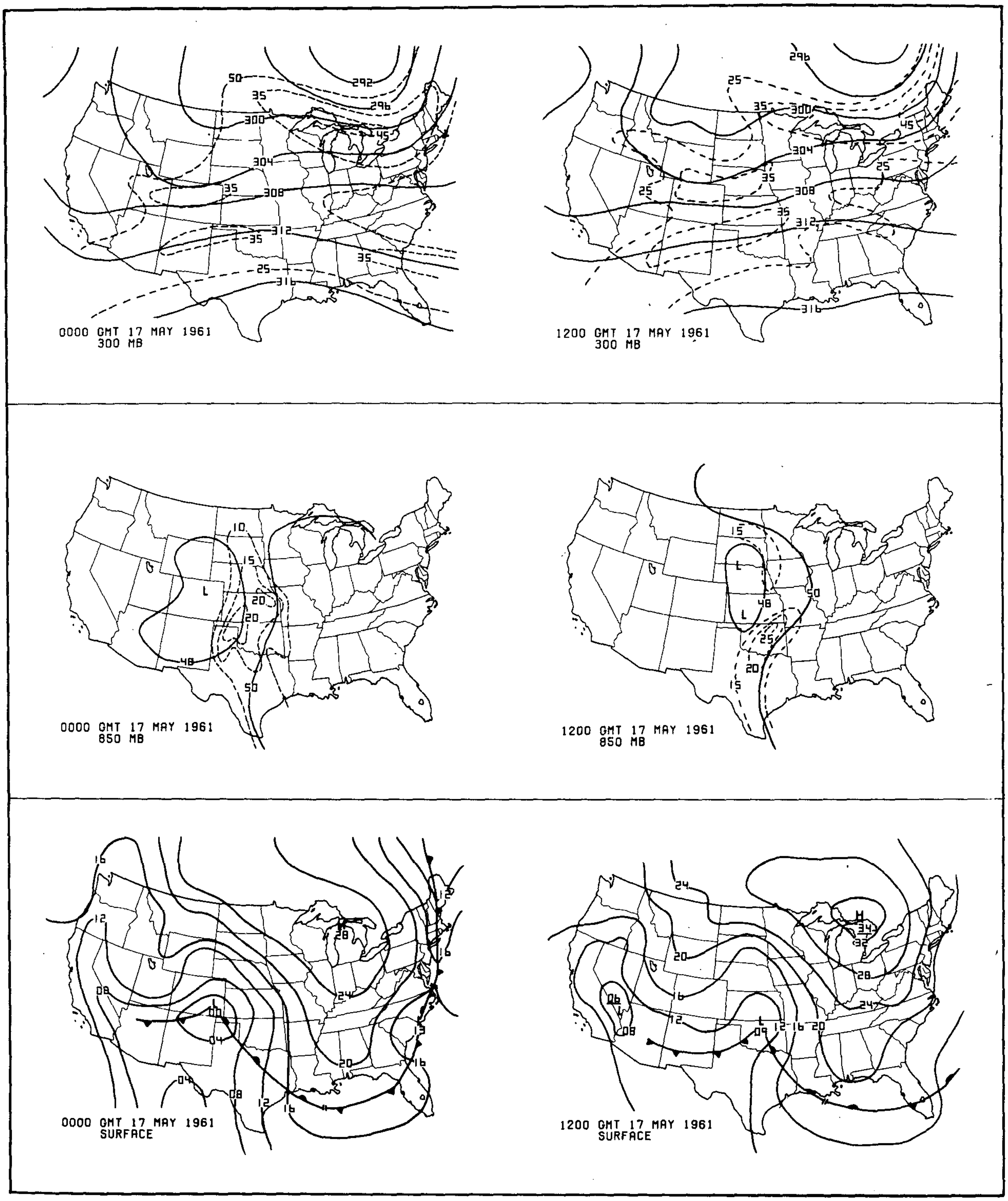

Fig. 5. National Weather Service 300 mb, 850 mb and surface analyses for 0000 GMT 17 May (left) and 1200 GMT 17 May 1961 (right). Isotachs are in meters per second, heights in geopotential feet.

suggesting that, even with significant subsynoptic-scale forcing, boundary-layer and terrain effects can still increase the magnitude of the LLJ in this region. Finally, the review of Bonner's case (1963, 1966) indicates that the evolution of the LLJ seems to be coupled to the propagation of an upper tropospheric jet streak and weakening leeside cyclone. The LLJ was located within the exit region of an upper level jet streak at two successive radiosonde observing periods and seemed to respond to an evolving surface pressure tendency field in a manner consistent with mutual mass-momentum adjustment concepts.

While the importance of boundary-layer and terrain effects in forcing the diurnal oscillation of the LLJ is evident in many cases, other factors besides boundary-layer processes should also be considered to explain the large number and evolution of the LLJ's observed in the southern Great Plains. One factor that has to be questioned is the concept that the westward extension or retrogression of the North Atlantic subtropical high creates the pressure gradient force needed for the development of the LLJ. At least for these cases of LLJ's, it appears that the high-pressure cell located in the southeast United States is of polar origin and that the pressure gradients increase over the Great Plains in response to a developing low pressure system to the west of the region rather than the retrogression of a high pressure system from the east. Given this type of synoptic- to subsynoptic-scale forcing in the Great Plains region, one must then question the assumption of imposing a constant pressure gradient or a diurnal variation in the pressure gradient for studying the total evolution of LLJ's in the Great Plains. Isallobaric wind concepts which account for the net mass adjustments above the PBL should be an important part of boundary-layer studies, in general (Young, 1973; Anthes *et al.*, 1980), and appear to be particularly important in the forcing of lower tropospheric wind maxima (e.g., Naistat and Young, 1971; Uccellini and Johnson, 1979).

The questions raised by this review can basically be summarized by comparing the climatological studies of LLJ's by Bonner (Fig. 1) and cyclogenesis by Petterssen (1956a; see Fig. 13.6.1) and Hovanec and Horn (1975). The coincidence of maxima for cyclogenesis and LLJ's to the lee of the Rocky Mountains, along the Texas Gulf Coast and along the East Coast of the United States suggests that the development of the LLJ could be closely linked with those processes that force cyclogenesis in the preferred geographic regions noted above. Statistical analysis such as that being completed by Horn *et al.* (1979) and additional detailed case studies are needed to prove that this correlation is significant and that subsynoptic-scale processes associated with upper level jet streaks and leeside cyclogenesis are indeed an important forcing mechanism for the development of LLJ's in the Great Plains.

REFERENCES

Anthes, R. A., N. L. Seaman and T. T. Warner, 1980: Comparisons of numerical simulations of the planetary boundary layer by a mixed-layer and multi-level model. *Mon. Wea. Rev.*, **108**, 365–376.

Blackadar, A. K., 1957: Boundary layer wind maxima and their significance for the growth of nocturnal inversions. *Bull. Amer. Meteor. Soc.*, **38**, 283–290.

Bonner, W. D., 1963: An experiment in the determination of geostrophic and isallobaric winds from NSSP pressure data. Res. Pap. 26, Mesometeorology Project, University of Chicago, 26 pp.

——, 1965: Statistical and kinematic properties of the low-level jet stream. Res. Pap. 38, Satellite and Mesometeorology Project, University of Chicago, 54 pp.

——, 1966: Case study of thunderstorm activity in relation to the low-level jet. *Mon. Wea. Rev.*, **94**, 167–178.

——, 1968: Climatology of the low-level jet. *Mon. Wea. Rev.*, **96**, 833–850.

Hoecker, W. H., 1963: Three southerly low-level jet streams delineated by the Weather Bureau special pibal network of 1961. *Mon. Wea. Rev.*, **91**, 573–582.

Horn, L. H., T. H. Achtor, and R. D. Hovanec, 1979: The mean upper tropospheric jet streak, associated low level jet and static stability for spring season Colorado cyclones. *Preprints Conf. Severe Local Storms*, Kansas City, Amer. Meteor. Soc., 104–107.

Hovanec, R. D., and L. H. Horn, 1975: Static stability and the 300 mb isotach field in the Colorado cyclogenetic area. *Mon. Wea. Rev.*, **103**, 628–638.

Izumi, Y., 1964: The evolution of temperature and velocity profiles during breakdown of a nocturnal inversion and a low-level jet. *J. Appl. Meteor.*, **3**, 70–82.

——, and M. L. Barad, 1963: Wind and temperature variations during development of a low-level jet. *J. Appl. Meteor.*, **2**, 668–673.

Lettau, H. H., 1967: Small to large scale features of boundary structures over mountain slopes. *Proc. Symp. Mountain Meteor.*, Colorado State University, 1–74.

Means, L. L., 1952: On thunderstorm forecasting in the central United States. *Mon. Wea. Rev.*, **80**, 165–189.

——, 1954: A study of the mean southerly wind maxima in low levels associated with a period of summer precipitation in the middle west. *Bull. Amer. Meteor. Soc.*, **35**, 166–170.

Naistat, R. J., and J. A. Young, 1973: A linear model of boundary layer flow applied to the St. Patrick's Day storm of 1965. *J. Appl. Meteor.*, **12**, 1151–1162.

Newton, C. W., 1956: Mechanisms of circulation change during a lee cyclogenesis. *J. Meteor.*, **13**, 528–539.

——, 1967: Severe convective storms. *Advances in Geophysics*, Vol. 12, Academic Press, 257–303.

Paegle, J., 1978: A linearized analysis of diurnal boundary layer convergence over the topography of the United States. *Mon. Wea. Rev.*, **106**, 492–502.

——, and G. E. Rasch, 1973: Three-dimensional characteristics of diurnally varying boundary-layer flows. *Mon. Wea. Rev.*, **101**, 746–756.

Petterssen, S., 1956a: *Weather Analysis and Forecasting*, Vol. 1. McGraw-Hill, 266–272.

——, 1956b: *Weather Analysis and Forecasting*, Vol. 2. McGraw-Hill, 191–195.

Reiter, E. R., 1969: Tropopause circulation and jet streams, *World Survey of Climatology*, Vol. 4, *Climate of the Free Atmosphere*, D. F. Rex, Ed., Elsevier, 85–193.

Uccellini, L. W., and D. R. Johnson, 1979: The coupling of upper and lower tropospheric jet streaks and implications for the development of severe convective storms. *Mon. Wea. Rev.*, **107**, 682–703.

Wexler, H., 1961: A boundary layer interpretation of the low-level jet. *Tellus*, **13**, 368–378.

Young, J. A., 1973: A theory for isallobaric air flow in the planetary boundary layer. *J. Atmos. Sci.*, **30**, 1584–1592.