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The Role of Upper Tropospheric Jet Streaks and Lee-Side 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 which developed in the Great Plains and which have been previously discussed in the literature is presented. The review notes that boundary layer processes were emphasized as causative factors in the development of the low level jet (LLJ) while upper tropospheric features were not considered and the importance of synoptic scale processes were generally minimized. For 12 out of the 15 cases, a systematic upper level flow pattern was 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 lee-side cyclogenesis or lee-side troughing that produces the pressure gradients needed for the development of the LLJ. For the other three cases, a blocking ridge existed over the Great Plains and the upper level flow was relatively weak. It is during these situations that the "classic," diurnal oscillating LLJ was observed. A more detailed review of four cases which used a special PIBAL network indicates that the subsynoptic scale forcing associated with the upper level jet streak's forcing of lee-side cyclogenesis could be an important factor in the development of LLJ's in the Great Plains. The review does not discount the importance of boundary layer processes which lead to the observed diurnal oscillation of the LLJ, but does question the notion that a retrogression of the subtropical high provides the increased pressure gradient force needed for the development of the LLJ in the Great Plains region.

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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 the low level (boundary layer) jet and upper tropospheric jet streak 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 showed that (1) a low-level jet beneath the exit region of an upper tropospheric jet streak was embedded in the lower branch of an indirect circulation, (2) the development of the LLJ was largely due to an increased lower tropospheric isallobaric wind component, and (3) the development of the LLJ was coupled to the upper tropospheric jet streak by a two-layer mass adjustment within the exit region of the streak. The Uccellini and Johnson case study illustrated the importance of subsynoptic scale processes in the development of a low level jet which subsequently produced the differential moisture and temperature advections that convectively destabilized the atmosphere and led to the development of severe convective storms.

The purpose of this technical memorandum is to explore the problem of applying the concept of coupled jet streaks to the large number of low level jets 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 if presented in Section 4.

2. LOW LEVEL JETS IN THE GREAT PLAINS

Bonner's (1968) statistical analysis confirmed that a large number of low level jets occur in the Great Plains, with the maximum number existing from Texas to Nebraska and a secondary maximum located along the North Carolina coast (Figure 1). Means (1952, 1954) and Bonner (1966) have shown 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 upon 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 may also develop in response to synoptic or subsynoptic scale processes particularly through a response to lee-side cyclogenesis common to the Great Plains. For the large number of jet cases collected for the climatological summary, Bonner (1963) stated that "On roughly 60 percent 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

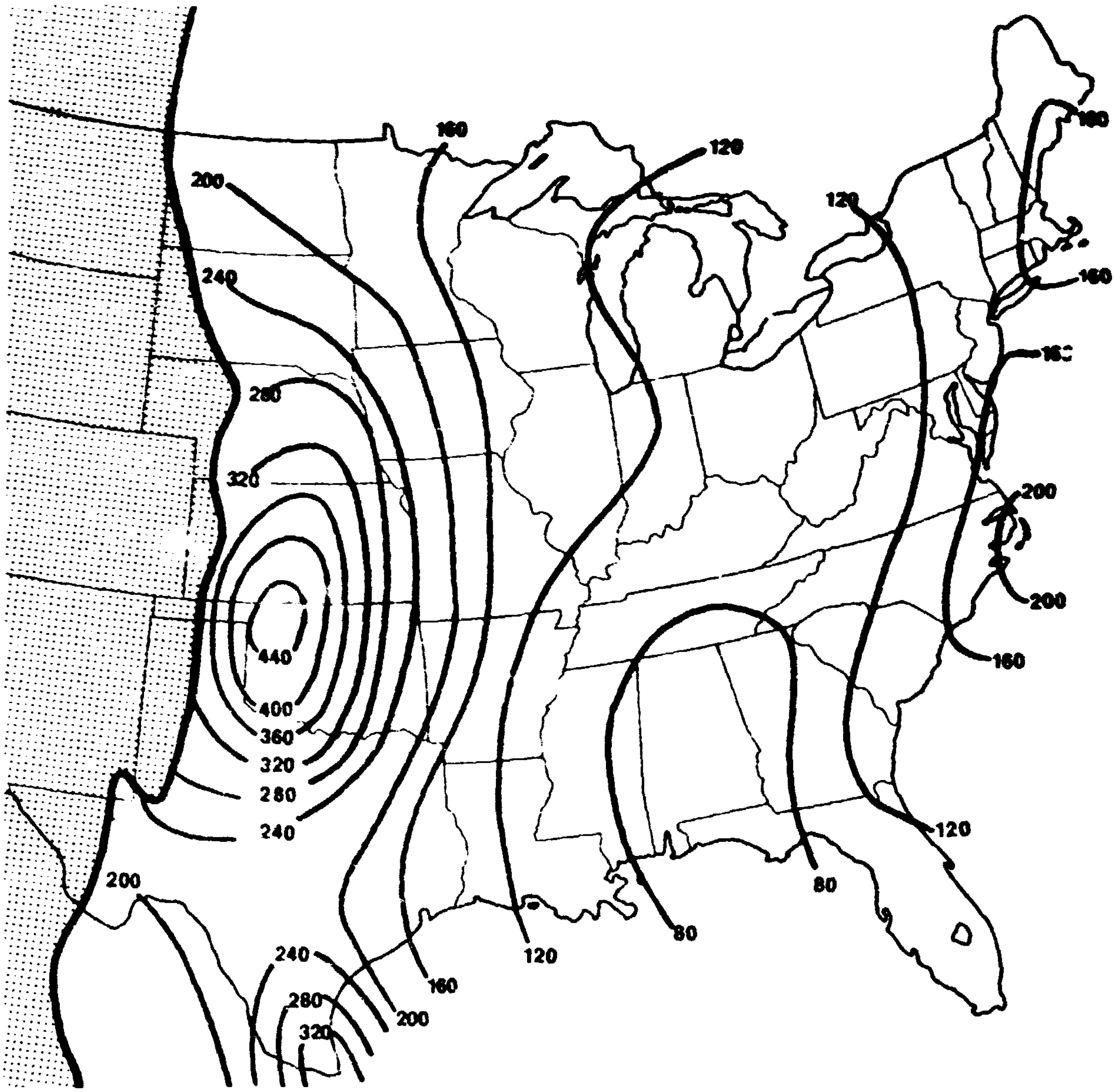

Figure 1. Number of low level jet observations from January 1959 through December 1960 at 1200 GMT and 0000 GMT. (From Bonner, 1965).

twelve hours." In a recent discussion, Bonner* 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) were frequently associated with lee-side troughing, lee-side cyclogenesis or a frontal passage associated with a cyclone further north. These observations suggest a correlation between LLJ occurrence and synoptic to subsynoptic scale forcing. They also serve as a motivation for reviewing cases of LLJ's previously reported in the literature for which boundary layer processes and terrain effects were emphasized and upper tropospheric and other synoptic features were not considered.

*Personal Communication

3. REVIEW OF LOW LEVEL JET CASE STUDIES

An extensive research effort into the forcing of low level jets was undertaken in the 1960's with special PIBAL networks and tower measurements essentially to test the theories previously presented by Blackadar (1957) and Wexler (1961). Table 1 lists 15 cases of LLJ's which were used in these studies and includes 4 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 lee-side cyclogenesis is listed in Table 1 since it also included 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.

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

NOTES: 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.

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 Figure 2 summarizes the upper tropospheric flow which prevailed during the occurrence of an LLJ and shows that two basic patterns existed for these cases. The first type consists of a trough over the Rockies and a 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 these 12

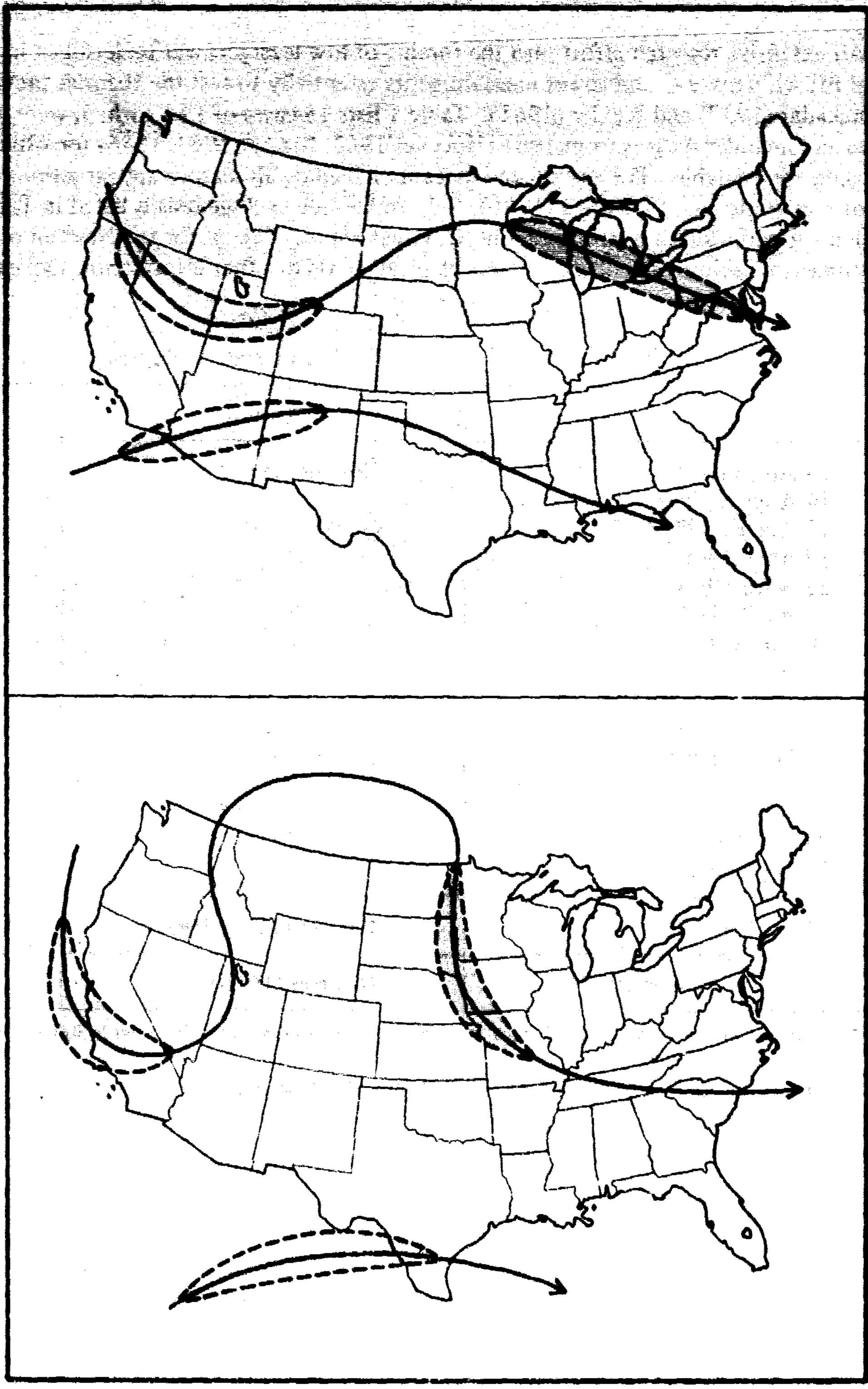

Figure 2. Schematic of upper tropospheric (300 mb) flow patterns for 15 cases of low level jets in the Great Plains. Top: Type 1 condition for 12 out of the 15 cases. Bottom: Type 2 condition for the other 3 cases. Shaded areas represent positions of upper level jet streaks.

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 lee-side 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 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) were 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 for 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 an LLJ in the southern Great Plains illustrates the "classic" diurnal oscillation in the magnitude and coherency of the LLJ (see Figure 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 (Figure 3). The 300 mb flow is also weak in the southern Great Plains with the height contours illustrating a Type 2 condition as 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 Figure 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 lee-side trough as the 300 mb trough shifted east from its 28 May position (Figure 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 lee-side 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 lee-side cyclone developed within the exit region of a jet streak, propagating toward the Great Plains from the Pacific Coast (Figure 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 Figure 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 lee-side 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 greater than 20 m s^{-1}. Although Hoecker attributed 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 cyclogenesis and the upper tropospheric jet streaks which are important for lee-side development (Newton

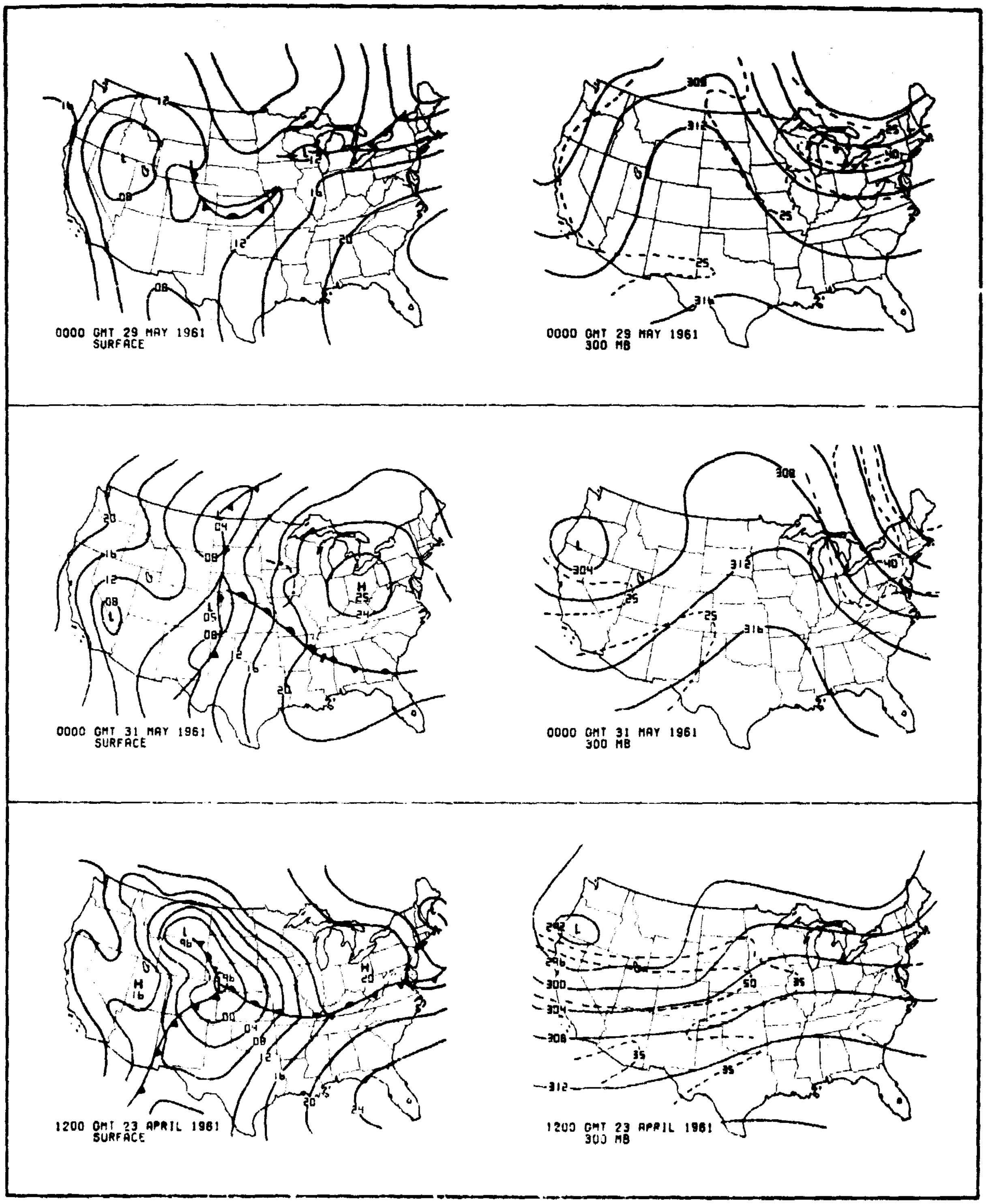

Figure 3. National Weather Service surface and 300 mb analyses for three cases of low level jets analyzed by Hoecker (1963). Top: 0000 GMT 29 May 1961; middle: 0000 GMT 31 May 1961; bottom: 1200 GMT 23 April 1961. Surface isobars are in mb (12 is 1012 mb); 300 mb heights are in geopotential feet (308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

1956; Hovenac and Horn, 1975) are more likely responsible for the strong pressure gradient in the Great Plains and persistent nature of the LLJ in 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 lee-side 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; Figure 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.

Figure 4 also includes the surface pressure tendencies computed over a 2-hour 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 Figure 4 represent inertial and isallobaric approximations to the ageostrophic wind (Uccellini and Johnson, 1979), which could be important in the development of the LLJ. It appears from Figure 4 that 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. Between 1800 GMT 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 southwest Missouri. The position of the LLJ also shifts southeast by 0000 GMT 17 May, then east, then northeast by 12 GMT 17 May, being consistently located within an area of maximum pressure falls analyzed 6 hours earlier.

The relative positions of the confluence zone and the pressure falls area 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 west approximated by the confluent streamlines and isallobaric wind (Figure 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 (Figure 4). The evolution of the wind, height and pressure tendency fields in this fashion is consistent with a mutual and continual mass-momentum adjustment occurring on a subsynoptic scale in association with the eastward propagation of the low pressure system.

The upper tropospheric features and synoptic scale characteristics of the 16–17 May 1961 case are illustrated in Figure 5. Between 0000 GMT and 1200 GMT, two upper tropospheric jet streaks propagated eastward into the Great Plains region. Lee-side cyclogenesis terminated by 0000 GMT 17 May as the surface low filled by 1200 GMT. The 850 mb maps in Figure 5 and the isotach maps at 0000 GMT and 1200 GMT 17 May in Figure 4 reveal that at both times the LLJ was located in the exit region of the southern-most upper level jet streak. Combining the information from Figures 4 and 5 suggests that the evolution of the LLJ and especially its eastward shift during the 12 h period (0000 GMT to 1200 GMT 17 May) is linked to the upper level jet's propagation and associated mass adjustments, as discussed by Uccellini and Johnson (1979). It would of course 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 GMT and 0600 GMT (Figure 4). However, it is quite evident that processes other than boundary layer inertial oscillations and retrograding sub-tropical highs are influencing lower tropospheric winds in this case.

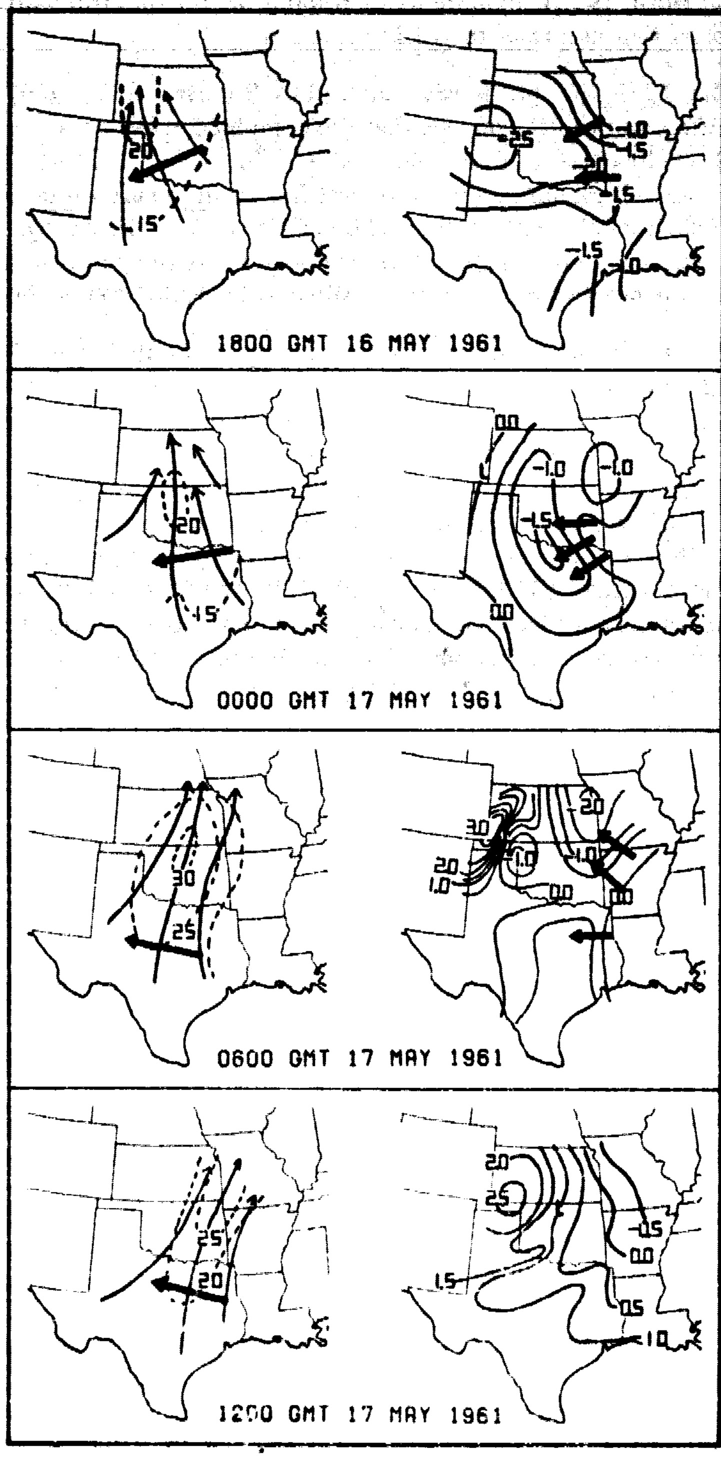

Figure 4. Isotach (ms^{-1}) and streamline analyses at the 1 km level (left) and surface pressure tendencies (mb/2 h) for the 16-17 May 1961 case study. Heavy lines represent an ageostrophic component related to confluent streamlines (left) and the isallobaric wind (right), both of which contribute to an along-stream acceleration for parcels entering the lower level jet. (From Bonner, 1963.)

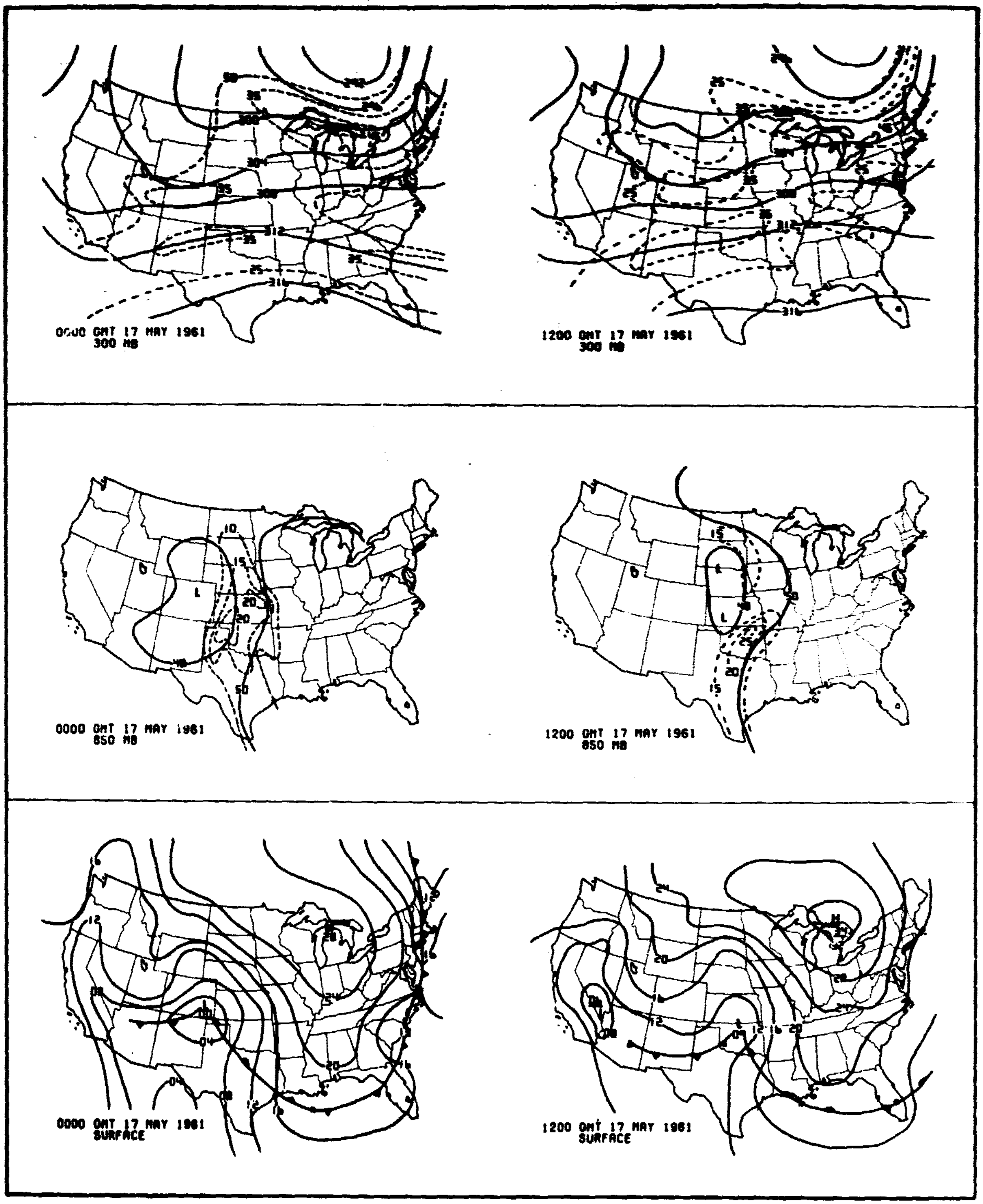

Figure 5. National Weather Service 300 mb, 850 mb, surface analyses for 0000 GMT 17 May (left) and 1200 GMT 17 May 1961 (right). Isotachs are in ms^{-1}, heights are in geopotential feet.

4. SUMMARY AND DISCUSSION

In this technical memorandum, 15 cases of LLJ's that were previously discussed in the literature were 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 12 out of the 15 cases the synoptic pattern was characterized by upper tropospheric jet streaks propagating toward the Great Plains from the Rocky Mountain area with the surface pressure gradients increased by lee-side cyclogenesis or lee-side troughing (Type 1 from Table 1). In these cases the LLJ's were located within the exit region of the upper level jet and directed toward the cyclonic side. In the other three cases, the upper troposphere over the Great Plains was characterized by a significant ridge and weak upper tropospheric flow (Type 2 from Table 1). The cases of well documented LLJ's characterized by the classic diurnal oscillation were associated with the Type 2 upper tropospheric pattern and relatively weak surface pressure gradients. The cases which had significant upper level jet streaks propagating toward the Great Plains and lee-side cyclogenesis had LLJ's which deviated from the classic pattern. In these cases, the LLJ was well defined, coherent, and more persistent even in the afternoon and extended beyond the planetary boundary layer. However, there was still a tendency for the maximum winds to be observed in the early morning, suggesting that even with significant synoptic 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) indicated that the evolution of the LLJ seems to be coupled to the propagation of an upper tropospheric jet streak and weakening lee-side cyclone. The LLJ was located within the exit region of an upper level jet streak at two successive radiosonde observing periods. The LLJ also seemed to respond to an evolving surface pressure tendency field in a manner consistent with mutual mass-momentum adjustment concepts.

It is suggested that the subsynoptic forcing associated with the upper tropospheric jet streaks role in lee-side cyclogenesis, as discussed by Newton (1956) and Hovenac and Horn (1975), are also important in the forcing of a large number of LLJ's in the southern Great Plains. While the importance of boundary layer and terrain effects in forcing the diurnal oscillation of the LLJ is evident, other factors besides boundary 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. Also evident is 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.

The questions raised by this review basically can be summarized by comparing the climatological studies of LLJ's by Bonner (Figure 1) and cyclogenesis by Petterssen (1956A; see Figure 13.6.1 on page 267) 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. Detailed statistical analysis such as that being completed by Horn, Achtor and Hovanec (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, lee-side cyclogenesis and lee-side troughing are indeed important forcing mechanisms for the development of LLJ's in the Great Plains.

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