AD-A106 159 AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH F/G 4/2
CYCLOGENESIS AND THE LOW-LEVEL JET OVER THE SOUTHERN GREAT PLAI--ETC(U)
DEC 80 D S LADWIG
UNCLASSIFIED AFIT-CI-80-78T NL

END
DATE
FILMED
11 81
DTIC

AD A106159

UNCLASS

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 80-78T	2. GOVT ACCESSION NO. AD-[illegible]	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Cyclogenesis & the Low-Level Jet Over the Southern Great Plains		5. TYPE OF REPORT & PERIOD COVERED THESIS/DISSERTATION
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) David Scott Ladwig		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS AFIT STUDENT AT: Texas A&M		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS AFIT/NR WPAFB OH 45433		12. REPORT DATE Dec 1980
		13. NUMBER OF PAGES 62
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASS
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

LEVEL

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

DTIC ELECTE OCT 26 1981 S D H

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

29 SEP 1981

FR. DRIC C. LYNCH, Major, USAF
Director of Public Affairs
Air Force Institute of Technology (ATC)
Wright-Patterson AFB, OH 45433

18. SUPPLEMENTARY NOTES

APPROVED FOR PUBLIC RELEASE: IAW AFR 190-17

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

ATTACHED

DTIC FILE COPY

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASS

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

ABSTRACT

Cyclogenesis and the Low-Level Jet
Over the Southern Great Plains. (December 1980)
David Scott Ladwig, B.S., Oklahoma State University
Chairman of Advisory Committee: Dr. Dušan Djurić

An investigation of the development of the low-level jet as an integral part of winter extratropical cyclones on the lee side of the Rocky Mountains during the winter months of 1977 and 1978 is presented. Twenty-nine cases of cyclogenesis were identified during the time period. Data for each case were tabulated, and, based upon the results of the study, four cases were chosen for closer examination. All cases were analyzed using standard synoptic methods supplemented by charts of the wind at the level of the maximum wind in the lower troposphere.

A descriptive model which shows the simultaneous development of the cyclone and low-level jet is presented. The formation of the low-level jet is shown to be partially a result of the geostrophic adjustment of initially isallobaric wind. This isallobaric wind results from pressure falls on the lee side of the Rocky Mountains during cyclogenesis.

The low-level jet originates over the high plains of western Oklahoma, Texas, and Kansas. As the southerly jet continues to develop, southerly wind spreads horizontally to the east and southeast with the speed of a gravity-inertia wave. Upon reaching the Gulf of

Mexico, low-level water vapor is advected by the jet into the southern Great Plains. The availability of water vapor and subsequently latent heat then contributes to the further development of the cyclone.

80-78T

AFIT RESEARCH ASSESSMENT

The purpose of this questionnaire is to ascertain the value and/or contribution of research accomplished by students or faculty of the Air Force Institute of Technology (ATC). It would be greatly appreciated if you would complete the following questionnaire and return it to:

AFIT/NR
Wright-Patterson AFB OH 45433

RESEARCH TITLE: Cyclogenesis & the Low-Level Jet Over the Southern Great Plains

AUTHOR: David Scott Ladwing

RESEARCH ASSESSMENT QUESTIONS:

1. Did this research contribute to a current Air Force project?

( ) a. YES ( ) b. NO

2. Do you believe this research topic is significant enough that it would have been researched (or contracted) by your organization or another agency if AFIT had not?

( ) a. YES ( ) b. NO

3. The benefits of AFIT research can often be expressed by the equivalent value that your agency achieved/received by virtue of AFIT performing the research. Can you estimate what this research would have cost if it had been accomplished under contract or if it had been done in-house in terms of manpower and/or dollars?

( ) a. MAN-YEARS ________ ( ) b. $________

4. Often it is not possible to attach equivalent dollar values to research, although the results of the research may, in fact, be important. Whether or not you were able to establish an equivalent value for this research (3. above), what is your estimate of its significance?

( ) a. HIGHLY SIGNIFICANT ( ) b. SIGNIFICANT ( ) c. SLIGHTLY SIGNIFICANT ( ) d. OF NO SIGNIFICANCE

5. AFIT welcomes any further comments you may have on the above questions, or any additional details concerning the current application, future potential, or other value of this research. Please use the bottom part of this questionnaire for your statement(s).

NAME GRADE POSITION

ORGANIZATION LOCATION

STATEMENT(s):

FOLD DOWN ON OUTSIDE - SEAL WITH TAPE

AFIT/NR
WRIGHT-PATTERSON AFB OH 45433

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE. $300

NO POSTAGE
NECESSARY
IF MAILED
IN THE
UNITED STATES

BUSINESS REPLY MAIL
FIRST CLASS PERMIT NO. 73236 WASHINGTON D.C.

POSTAGE WILL BE PAID BY ADDRESSEE

AFIT/ DAA
Wright-Patterson AFB OH 45433

FOLD IN

CYCLOGENESIS AND THE LOW-LEVEL JET OVER THE SOUTHERN GREAT PLAINS

A Thesis

by

DAVID SCOTT LADWIG

Submitted to the Graduate College of
Texas A&M University
in partial fulfillment of the requirement for the degree of

MASTER OF SCIENCE

December 1980

Major Subject: Meteorology

CYCLOGENESIS AND THE LOW-LEVEL JET

OVER THE SOUTHERN GREAT PLAINS

A Thesis

by

DAVID SCOTT LADWIG

Approved as to style and content by:

(Chairman of Committee)

(Head of Department)

(Member) (Member)

December 1980

ABSTRACT

Cyclogenesis and the Low-Level Jet
Over the Southern Great Plains. (December 1980)
David Scott Ladwig, B.S., Oklahoma State University
Chairman of Advisory Committee: Dr. Dušan Djurić

An investigation of the development of the low-level jet as an integral part of winter extratropical cyclones on the lee side of the Rocky Mountains during the winter months of 1977 and 1978 is presented. Twenty-nine cases of cyclogenesis were identified during the time period. Data for each case were tabulated, and, based upon the results of the study, four cases were chosen for closer examination. All cases were analyzed using standard synoptic methods supplemented by charts of the wind at the level of the maximum wind in the lower troposphere.

A descriptive model which shows the simultaneous development of the cyclone and low-level jet is presented. The formation of the low-level jet is shown to be partially a result of the geostrophic adjustment of initially isallobaric wind. This isallobaric wind results from pressure falls on the lee side of the Rocky Mountains during cyclogenesis.

The low-level jet originates over the high plains of western Oklahoma, Texas, and Kansas. As the southerly jet continues to develop, southerly wind spreads horizontally to the east and southeast with the speed of a gravity-inertia wave. Upon reaching the Gulf of

Mexico, low-level water vapor is advected by the jet into the southern Great Plains. The availability of water vapor and subsequently latent heat then contributes to the further development of the cyclone.

ACKNOWLEDGEMENTS

The financial support for the author's graduate program was provided by the United States Air Force under sponsorship of the Air Force Institute of Technology.

I would like to express my gratitude to Dr. Dusan Djuric for his guidance, encouragement, and assistance in the preparation of this study. Sincere thanks are also extended to Professor W. K. Henry and Dr. T. W. Spence for their helpful comments which made the completion of this study possible.

DEDICATION

This thesis is dedicated to my wife,
Beth, and my daughter, Danielle,
whose patience and understanding
made this work possible.

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

a. General

The movement of cyclones through the southern Great Plains provides the mechanism for a substantial amount of precipitation received in the southern Great Plains during the winter months. As these cyclones originate on the lee side of the Rocky Mountains, low-level water vapor is advected from the Gulf of Mexico into the southern Great Plains by low-level winds. At times, the low-level winds form in bands with the maximum wind being over 12.5 m s^{-1}, thus are called low-level jets (LLJ). While the LLJ advects low-level water vapor into the Great Plains and cyclones moving through the Great Plains are responsible for most of the precipitation received in the region, little has been said about the apparent relationship between cyclones and LLJ development. The purpose of this research is to document this relationship between cyclogenesis and the development of the LLJ in the winter months.

b. Literature review

In his discussion of circulation changes associated with cyclogenesis, Newton (1956) cited the existence of a LLJ which hugged the eastern slopes of the Rocky Mountains during cyclogenesis. Later (1967), he showed a model of an idealized cyclone moving through the

---

The citations on the following pages follow the style of the Journal of Applied Meteorology.

Great Plains. This model included a moist tongue coincident with a LLJ.

A number of authors have discussed the advection of water vapor in the lower levels of the atmosphere from the Gulf of Mexico into the Great Plains. Much of the work has dealt with the transformation of polar air masses which move over the Gulf of Mexico and then return into the Great Plains. Henry and Thompson (1976) and Karnavas (1978) discussed sensible and latent heat flux from the Gulf of Mexico into the polar air mass and the transformation of the polar air that resulted. Karnavas (1978) continued by showing that the entry of low-level cloudiness into the southern Great Plains was closely tied to the movement of the polar anticyclone to the northeast. Henry (1979) proposed a system by which polar air entering the southern Great Plains could be differentiated from tropical air through the use of equivalent temperature and wind direction.

Damiani (1979) showed that the rapid entry of water vapor in the lower levels was closely tied to the development of a low-level wind maximum in the polar air mass. This maximum developed over the high plains of western Texas, Oklahoma, and Kansas shortly after the polar air mass reached the northern Gulf of Mexico. Djurić and Damiani (1980) showed that after development over the high plains, the LLJ spread horizontally, eventually reaching the northern Gulf of Mexico. The entry of low-level water vapor into the southern Great Plains coincided with the southern extension of the LLJ reaching the Gulf. While this study deals with the winter months, Beckman (1973) found several cases of LLJ formation in a polar air mass during the spring months.

Three basic causes have been proposed for the formation of the LLJ by authors investigating the phenomenon. Blackadar (1957) proposed a theory that described the coupling and decoupling of flow near the top of the frictional boundary layer. The coupling and decoupling of the flow was caused by the formation and destruction of the nocturnal inversion. When this occurred, an inertial oscillation of the ageostrophic wind vector could be identified. This oscillation coincided with the formation of low-level wind maxima. Wexler (1961) identified a cause of LLJ formation as the northward deflection of easterly currents by the Rocky Mountains. As these winds were deflected to the north, the increase in coriolis force was compensated for by a strong increase in anticyclonic shear on the eastern side of the stream, satisfying the law governing the conservation of absolute vorticity. Frictional influences from the sloping terrain on the western side of the flow accounted for the shear on the western side of the stream. A third cause, proposed by Holton (1967), showed that the LLJ could be explained by the combined circulations of air associated with heating and cooling of the slopes of the Rocky Mountains and high plains, and the baroclinic field that resulted from this heating and cooling.

Climatological studies have shown the occurrence of low-level wind maxima to be most prevalent in the southern Great Plains (Bonner, 1968). The same study showed that the greatest number of LLJs occurred during the spring and summer months, but there were a substantial number of occurrences during the winter months. This study also established convenient criteria to define the existence of the LLJ.

Tepper (1955) developed a model which showed that through the addition of momentum to a narrow southerly stream, a low pressure trough developed to the left of the stream. He also showed that through the addition of momentum, pressure-jump lines developed and propagated to the right of the stream. Djurić (1980) proposed a model of a LLJ which developed under an inversion as a result of decreasing pressure to the left of the LLJ. He suggested that the initiation of the LLJ resulted from isallobaric winds and their subsequent geostrophic adjustment. The isallobaric winds were brought about by decreasing pressure on the lee side of the Rocky Mountains. This model showed that a perturbation developed within or below an inversion layer. This perturbation then moved horizontally to the east and southeast with the speed of a gravity-inertia wave. The initiation of a southerly wind occurred after the passing of the perturbation over a station.

The papers of Tepper (1955), Newton (1956), and Djurić (1980) indicate that a connection between the development of a LLJ and the cyclogenesis process on the lee side of the Rocky Mountains exists. The work of previous authors deals with the phenomenon of the development of cyclones and LLJs separately, but there appears to be a strong link between the two processes. This study will show the interrelationship between the two phenomena and propose a model which describes the simultaneous development of the cyclone and the LLJ which precedes the development time shown in Newton's (1967) model.

2. HYPOTHESIS OF LOW-LEVEL JET DEVELOPMENT

If simultaneous development of a cyclone and associated LLJ can be shown, a cause for LLJ development can be hypothesized. The LLJ may develop in response to acceleration induced by pressure fall on the lee side of the Rocky Mountains. The pressure fall results from large scale cyclogenesis.

Djurić and Damiani (1980) showed that the LLJ is observed in a layer normally within 2 km of the earth's surface. The LLJ was observed above the frictional boundary layer described by Blackadar (1957). The flow is governed by the horizontal equations of motion:

$$\frac{du}{dt} = fv - \frac{1}{\rho}\frac{\partial p}{\partial x}$$

and

$$\frac{dv}{dt} = -fu - \frac{1}{\rho}\frac{\partial p}{\partial y} .$$

Frictional terms are omitted since the LLJ develops above the frictional boundary layer where frictional effects are negligible compared to the remaining terms. If the assumption of acceleration due to pressure fall is made then an approximate solution to the above equations is:

$$u = -\frac{1}{\rho f}\frac{\partial p}{\partial y} + \frac{1}{\rho f^2}\frac{\partial}{\partial y}\left(\frac{\partial p}{\partial t}\right)$$

and

$$v = \frac{1}{\rho f}\frac{\partial p}{\partial x} + \frac{1}{\rho f^2}\frac{\partial}{\partial x}\left(\frac{\partial p}{\partial t}\right) .$$

As pressure falls on the lee side of the Rocky Mountains during cyclogenesis, the wind over the High Plains responds to an isallobaric acceleration. At this time, the isallobaric terms are dominant in the equations. After some time, geostrophic adjustment takes place and the geostrophic terms in the above equations become dominant. This time was shown by Cahn (1945) and Obukhov (1949) to be approximately 6 h. As geostrophic adjustment takes place, southerly wind is observed over the High Plains. As pressure continues to fall, the southerly wind strengthens over the High Plains, taking the appearance of a LLJ.

3. METHODOLOGY

The methodology used in this study of cyclogenesis and the LLJ evolved from earlier investigations of these phenomena by other authors. Isallobaric analysis at the surface during the development of a cyclone and the associated LLJ showed similar patterns in each case; pressure falls accompanied cyclone development on the lee side of the Rocky Mountains. Since there appeared to be a possible correlation between the developing LLJ and the isallobaric field, cases were chosen based upon pressure falls on the lee side of the Rocky Mountains. Since large pressure falls are sometimes observed during cyclogenesis, cyclone development was used as a criterion for the selection of cases. If there is a correlation between the development of a cyclone and the occurrence of the LLJ, it should be possible to develop a model which shows the relationship between these phenomena.

a. Selection of cases

The criteria listed below were used to select cases.

(1) Low pressure developed on the lee side of the Rocky Mountains. Each low pressure area was identified by at least one closed isobar (4mb) on the National Meteorological Center surface analysis.

(2) The low pressure area had to develop into a frontal cyclone and move into the Great Plains.

Based upon the above criteria, cases were selected from microfilm reels of the northern hemispheric surface charts supplied by the

National Climatic Center. In this study, low pressure development on the lee side of the Rocky Mountains refers to development in eastern Colorado, western Kansas or Oklahoma, northern New Mexico, or northwest Texas. Cases were selected from the winter months of January through March, and October through December during 1977 and 1978.

Thirty-two cases of cyclogenesis were identified based upon the above criteria. Each of the cases was examined further through the use of National Meteorological Center facsimile charts and Service A and C teletype data. Three cases were discarded due to missing or garbled teletype or facsimile data. Facsimile and teletype data were obtained from those currently available in the archives of the Department of Meteorology at Texas A&M University.

b. Analysis procedure

National Meteorological Center facsimile charts were used when possible to identify upper-air features coincident with early development of the cyclone. A detailed surface analysis was made at each upper-air radiosonde sounding time (0000 and 1200 GMT). Special attention was paid to the position of fronts and high and low pressure areas. Isallobaric and isodrosothermic analysis also was done. Additional surface charts were analyzed as necessary to describe a given case in greater detail than that available on the three-hourly National Meteorological Center surface charts. As shown by Bonner (1968), and Djurić and Damiani (1980), the LLJ may not be apparent on either the National Meteorological Center 850 mb or 2nd Standard Level charts. To identify the existence and the horizontal extent of the LLJ, charts were prepared which identify the wind direction and speed at the level of the maximum wind in the lowest 2 km of the atmosphere. The following events were used in the selection of a maximum wind with the indicated priority:

(1) Highest wind speed below a frontal or subsidence inversion within 2 km of the surface, or,

(2) Highest wind speed within 2 km of the surface.

If more than one inversion existed, the inversion used was the one most similar to the inversion above neighboring stations. Care was used to ascertain if the highest wind speed selected was representative of those characteristics normally associated with a LLJ. To identify the highest wind speed chosen as representative of the LLJ, the highest wind speed must have exceeded the wind speeds at levels above and below the level of the highest wind speed chosen by at least 2.1 m s^{-1}.

4. WEATHER SITUATIONS

a. Data tabulation

Each of the 29 cases of cyclone development on the lee side of the Rocky Mountains was examined for the characteristics listed below. The results of the data tabulation were then used to identify those characteristics which were common throughout the majority of cases. Characteristics were chosen based upon those items which were identified by previous authors investigating the development of the LLJ or cyclogenesis. Results of the data tabulation are shown in Table 1. A description of column headings is given below.

(1) Category of LLJ development. Each case of cyclone development was examined for the presence of a LLJ. The category "Strong" represents those cases where the LLJ core speed exceeded 12.5 m s^{-1}. Also, at least 60% of the stations which had an observed LLJ had to have an observed inversion capping the LLJ. The category is similar to the Category 1 identified by Bonner (1968). The category "Weak" indicates those cases where the observed LLJ core speed was less than 12.5 m s^{-1}. The category "None" indicates that no LLJ was observed.

(2) 700 mb flow direction. This characteristic identifies the flow direction over the area of initial cyclone development. This characteristic may be related to cyclone development.

(3) Cyclone development and duration. The initial and lowest central cyclone pressures are given as well as the duration of the cyclone while in the southern Great Plains. Cyclone duration while in the southern Great Plains refers to an area bounded on the east by

Table 1. Cases of cyclone development during 1977 and 1978.

Date	Category of LLJ Development Strong	Weak	None	700 mb Flow Direction From	Cyclone Development Init (mb)	Low (mb)	Dur (h)	Moist Adv*
				1977				
3-4 Jan			X	W	1004	999	36+	no
21-23 Feb	X			NW	984	976	24+	yes
25-26 Feb	X			W	1005	998	36+	yes(r)
10-11 Mar	X			SW	993	985	30+	yes
16-17 Mar	X			W	1000	987	30+	yes
20-21 Mar	X			NW	1006	1002	36+	yes
3-4 Oct	X			NW	1011	1000	27	yes
9-10 Oct	X			W	1006	1002	36	yes
27-28 Oct		X		SW	1008	1007	45	yes
29-30 Oct		X		SW	1009	999	16	yes
18-21 Nov	X			NW	1006	992	48+	yes
4-5 Dec		X		W	1001	990	48+	yes(r)
7-8 Dec	X			W	1006	994	27+	yes
10-12 Dec	X			W	1011	999	36+	yes
18-19 Dec			X	W	1003	996	36	yes
				1978				
6-8 Jan			X	NW	1007	1005	30+	yes
14-16 Jan	X			NW	1014	1002	48+	yes
1-3 Mar	X			NW	999	998	30+	yes(r)
5-6 Mar	X			W	1008	1000	48	yes
10-11 Mar	X			W	1009	998	42+	yes
12-14 Mar	X			NW	999	996	30+	yes
1-3 Oct	X			W	1008	1007	30+	no
17-18 Oct	X			SW	1010	1010	18	no
21-23 Oct	X			SW	1004	1004	30+	no
24-25 Oct	X			W	998	995	18	yes
8-10 Nov	X			NW	1003	996	36+	yes
24-26 Nov	X			W	1008	1002	36+	yes
17-20 Dec	X			NW	1004	995	30+	yes
27-29 Dec	X			W	1013	997	30+	yes

* (r) means that residual low cloudiness was observed throughout the southern Great Plains which made the determination of advective processes difficult.

the eastern Kansas and Oklahoma borders, and to the north by the northern Nebraska border.

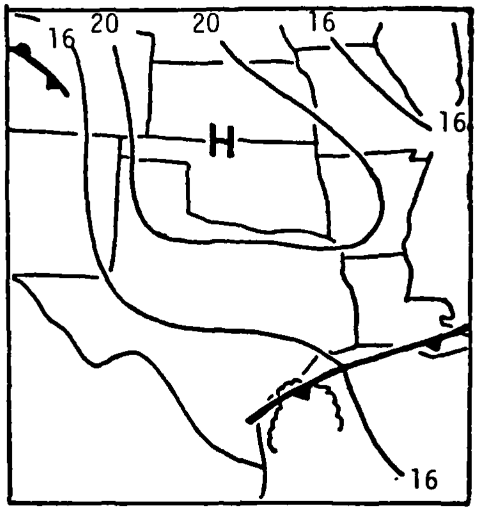
(4) Low-level cloudiness or moist tongue. This characteristic identifies the expansion of low-level cloudiness from Gulf coastal regions into the southern Great Plains, or the advection of water vapor into the area as indicated by a moist tongue in a surface isodrosotherm analysis.

Three cases are not shown in the table due to missing or garbled data. These cases were 5-8 November 1977, 26-28 November 1977, and 3-5 January 1978.

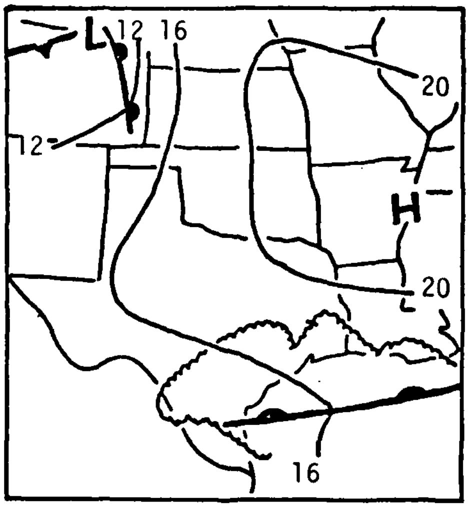
b. Selected case studies

From the 26 cases tabulated where there was simultaneous development of a cyclone and a LLJ, four typical cases were chosen for closer examination based upon observed characteristics. Although the cases chosen are similar to the remaining 22 cases, these cases emphasize variations such as timing in the development, duration of a case, strength of the cyclone or LLJ, and the advective processes present. The surface maps shown in each case are those analyzed by the National Meteorological Center.

(1) 18-20 November 1977. One of the typical cases of simultaneous development of the cyclone and associated LLJ occurred on 18-20 November 1977. Fig. 1a shows the surface weather situation at 0000 GMT 18 November 1977. A stationary front was located in central Colorado with high pressure over northern Oklahoma. There was weak southerly flow at the surface on the lee side of the Rocky Mountains



a. 0000 GMT 18 November 1977



b. 0900 GMT 18 November 1977

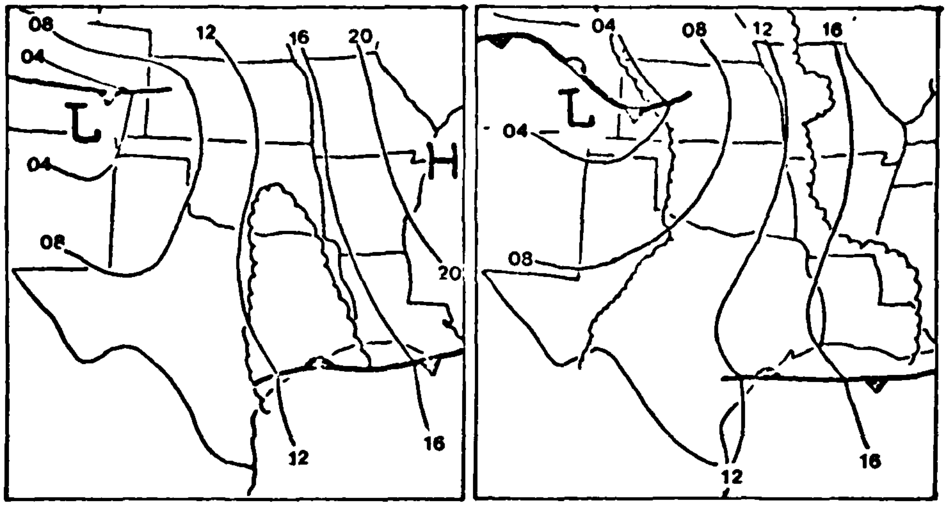
Fig. 1. Surface synoptic charts. Scalloped areas indicate areas of cloudiness at a height of less than or equal to 900 m (3000 ft) AGL.

while flow at 700 mb and 500 mb was from the northwest. At 850 mb, a weak trough was located over Utah and Arizona. During the night, pressure fell throughout the southern lee side of the Rocky Mountains. By 0900 GMT, a closed low pressure area developed along the stationary front in central Colorado (Fig. 1b). During this period, flow in the mid- and upper-levels became zonal. Also, the LLJ developed over the high plains during this time.

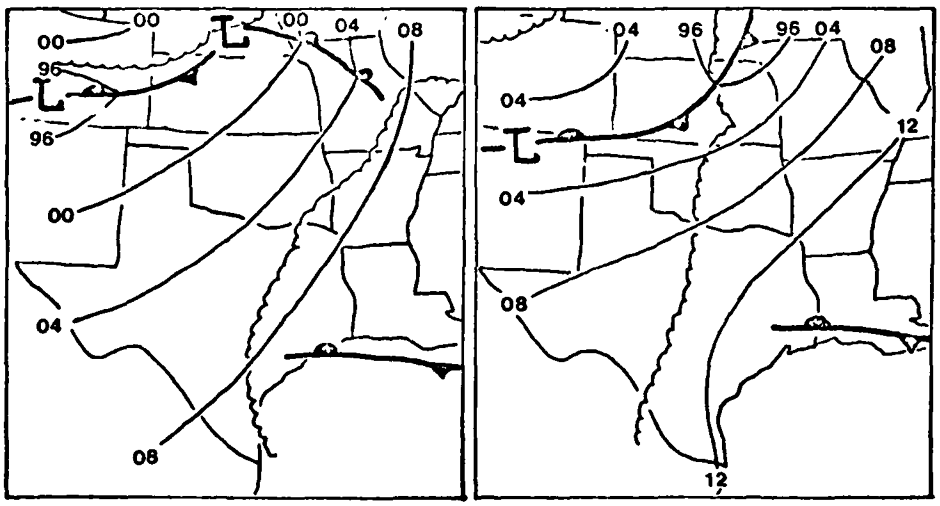
Subsequent development and movement of the cyclone is shown in Figs. 2a-d. As the cyclone developed, an area of low cloudiness expanded from the Gulf of Mexico into the southern Great Plains. This expansion of low cloudiness was coincident with the southern extension of the LLJ reaching an area over the northern Gulf of Mexico. The development and movement of the LLJ is shown in Figs. 3a-d.

The cyclone continues to develop on 19 November 1977 as the mid- and upper-level flow becomes southwesterly as an upper-air trough approaches. On 20 November 1977, the cyclone moves through the Great Plains to the northeast. The cyclone duration exceeded 60 h, and the cyclone had a minimum observed central pressure of 990 mb. During this time, the LLJ maintained its vertical and horizontal definition as it moved to the east in advance of the cyclone. During the episode, the LLJ had a maximum observed core speed of 23 m s^{-1} and was observed in the polar air mass at a continuous height of approximately 0.5-1 km.

As a result of the LLJ, the thermal contrast, baroclinity, and availability of water vapor for precipitation processes was increased. This case appears to be rather typical of the winter cyclones studied

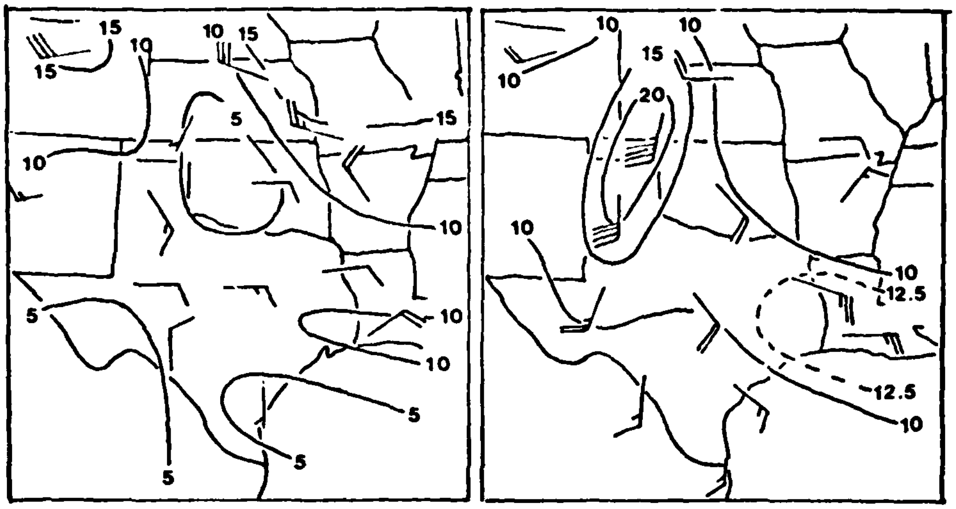


a. 0000 GMT 19 November 1977 b. 1200 GMT 19 November 1977

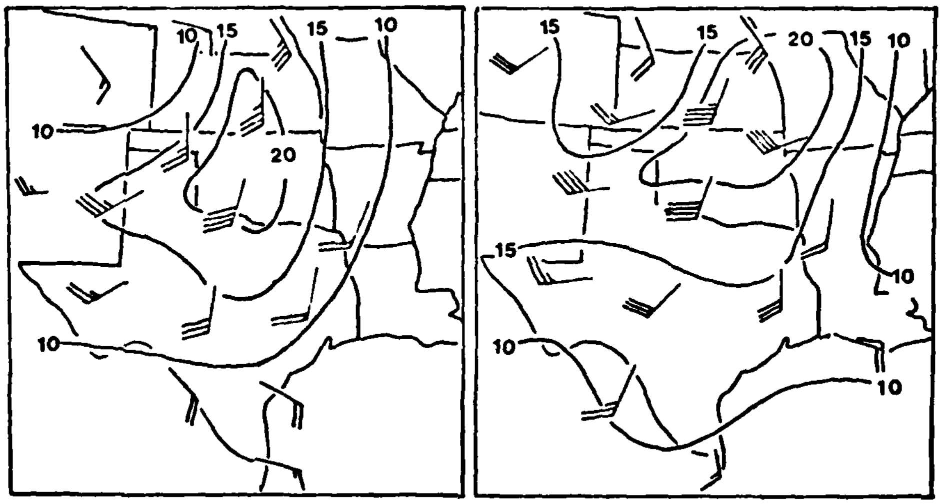


c. 0000 GMT 20 November 1977 d. 1200 GMT 20 November 1977

Fig. 2. Same as Fig. 1 except on 19-20 November 1977.



a. 0000 GMT 18 November 1977 b. 1200 GMT 18 November 1977



c. 0000 GMT 19 November 1977 d. 1200 GMT 19 November 1977

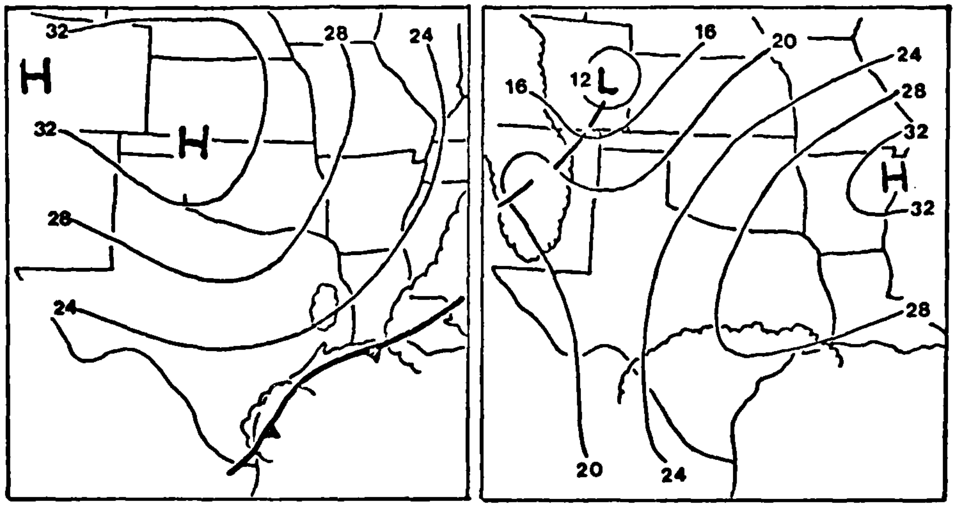
Fig. 3. Isotach analysis (m s^{-1}) at the level of the maximum wind in the lowest 2 km of the atmosphere. Each wind barb represents 5 m s^{-1}.

in the sense that the LLJ seems to be an important part of the winter extratropical frontal cyclone developing on the lee side of the Rocky Mountains.

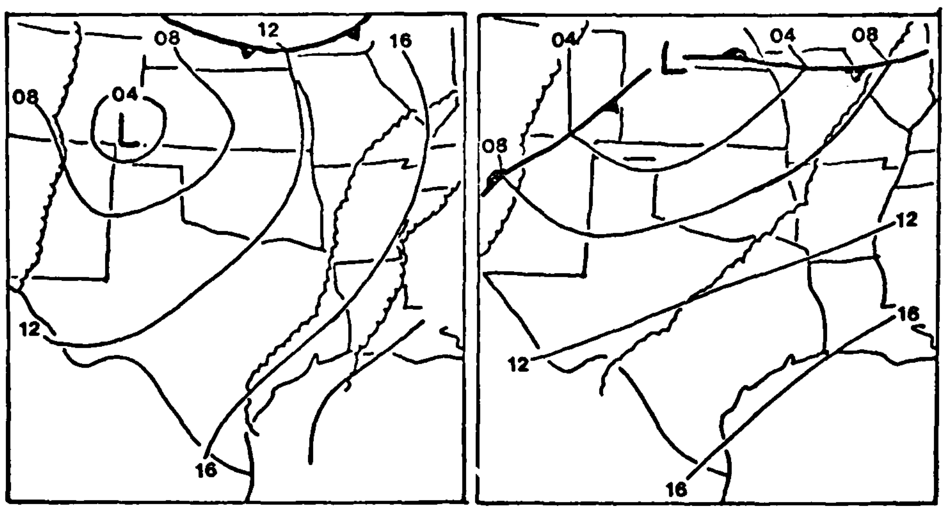
(2) 17-20 December 1978. Coincident development of a cyclone and the LLJ occurred. Fig. 4a shows the weather situation at the surface on 17 December 1978. A strong polar anticyclone was located over the central United States at the surface. A high pressure ridge was located over the Great Plains at 850 mb, while the flow at 700 mb and 500 mb was zonal to northwesterly over the lee side of the Rocky Mountains. Pressure fell on the lee side of the Rocky Mountains during the next 48 h, and a closed low pressure area developed at 0000 GMT 18 December 1978 (Fig. 4b-c). During the latter portion of the 48 h period, mid- and upper-tropospheric flow became southwesterly over the lee side of the Rocky Mountains, and there was weak positive vorticity advection at 500 mb over the area of cyclone development.

By 1800 GMT 19 December 1978 (Fig. 4e), the central cyclone pressure was 1000 mb, and the cyclone began to move to the east. Unlike the case of 18-20 November 1977, low-level cloudiness was not observed in the southern Great Plains, but was observed over Texas Gulf coastal areas throughout the period. Although low-cloudiness was not observed over the southern Great Plains, a moist tongue was present at the surface indicating that the advection of low-level water vapor occurred in the southern Great Plains. Subsequent development and movement of the cyclone is shown in Fig. 4f.

Development of the LLJ is shown in Figs. 5a-d. As the cyclone

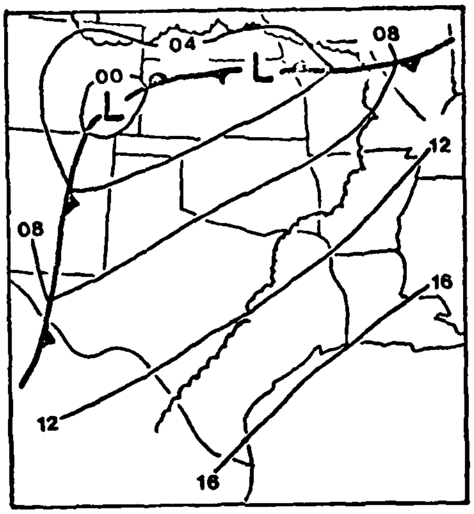


a. 0000 GMT 17 December 1978 b. 0000 GMT 18 December 1978

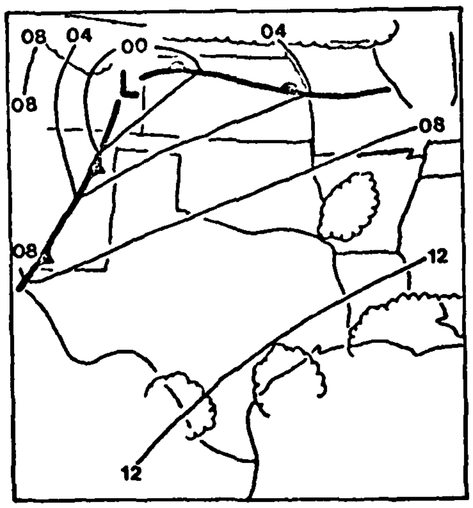


c. 0000 GMT 19 December 1978 d. 1200 GMT 19 December 1978

Fig. 4. Same as Fig. 1 except for 17-20 December 1978.

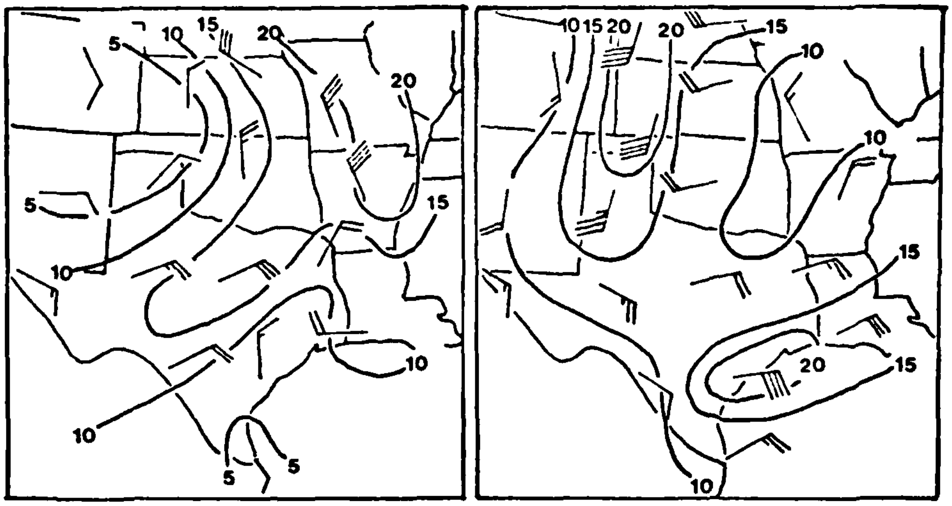


e. 1800 GMT 19 December 1978

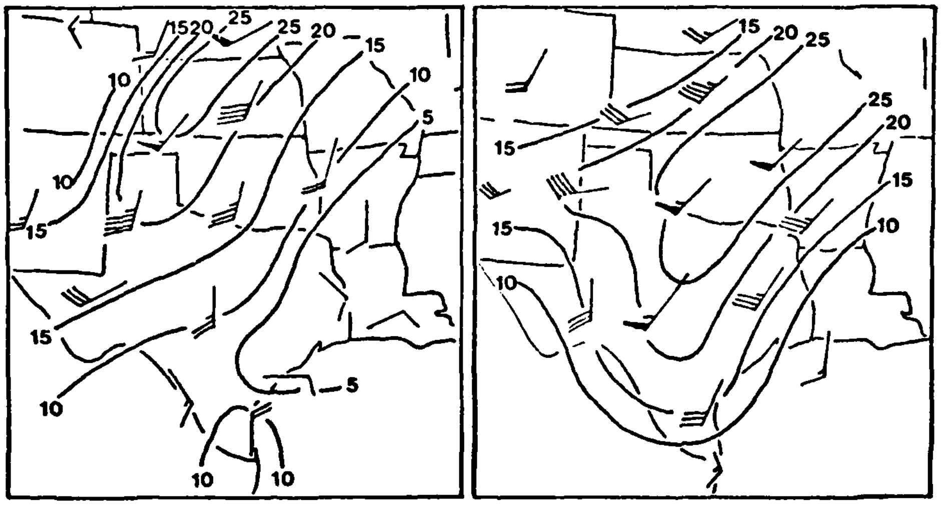


f. 0000 GMT 20 December 1978

Fig. 4. Continued.



a. 0000 GMT 17 December 1978   b. 1200 GMT 17 December 1978



c. 0000 GMT 18 December 1978   d. 1200 GMT 18 December 1978

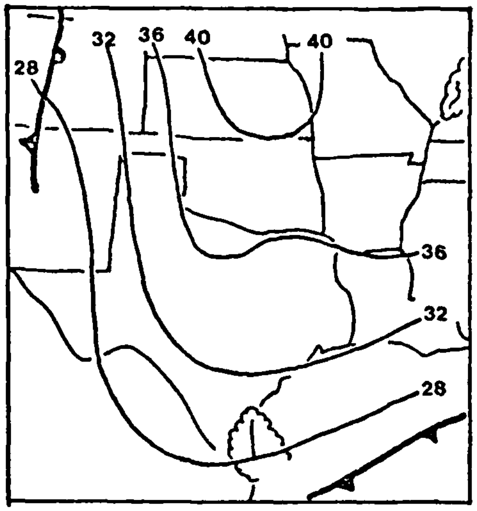
Fig. 5. Same as Fig. 3 except for 17-18 December 1978. The pennant represents 25 m s^{-1}.

moved to the east, southerly wind at the LLJ level spread horizontally. The southern extension of the LLJ, upon reaching the Gulf, advected low-level water vapor into the southern Mississippi Valley on 20 December 1978. Low cloudiness reported in southern Texas during the early portion of the period occurred beneath the wind observed at the level of the maximum wind in the lowest 2 km of the atmosphere. During the period, the LLJ was observed in the polar air mass and had an observed maximum core speed of 27.5 m s^{-1}. The cyclone attained a minimum central pressure of 994 mb as it moved through the Great Plains. The height of the LLJ was continuous at approximately 0.5 km above the surface early in this case and rose to a height of 1 km as the LLJ core moved into central Oklahoma.

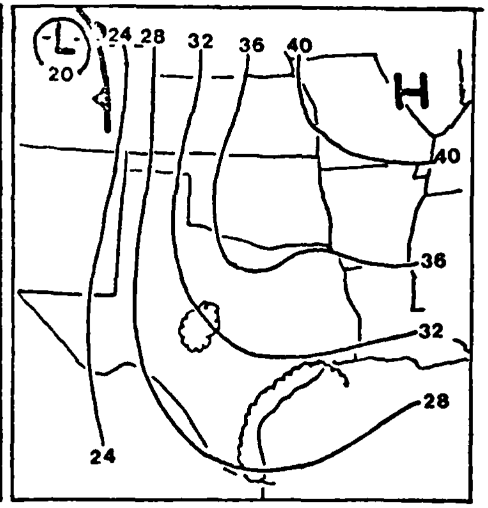
Although there is simultaneous development of the LLJ and the cyclone, this development process is somewhat slower than in the previous case. This case also emphasizes that if an expansion of areas of low cloudiness into the southern Great Plains is not present, a surface isodrosotherm analysis should be made to identify the advection of low-level water vapor by the LLJ in the extratropical cyclone.

(3) 10-13 December 1977. As in the previous case, a strong polar anticyclone was located over the southern Great Plains. Again there was simultaneous development of the cyclone and LLJ, but the development process is somewhat faster and the advection of low-level water vapor more evident than in the previous case.

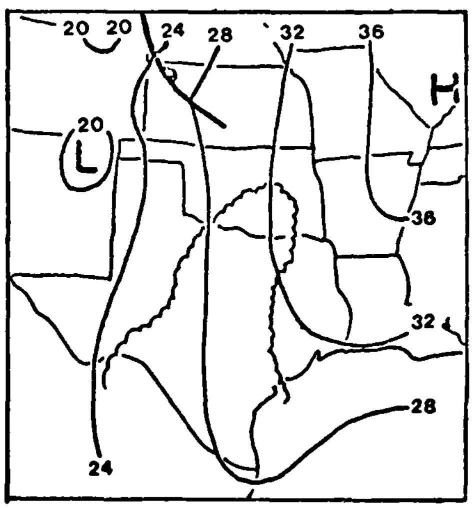
Fig. 6a shows the surface weather situation on 10 December 1977. A strong polar anticyclone had moved into the southern Great Plains.



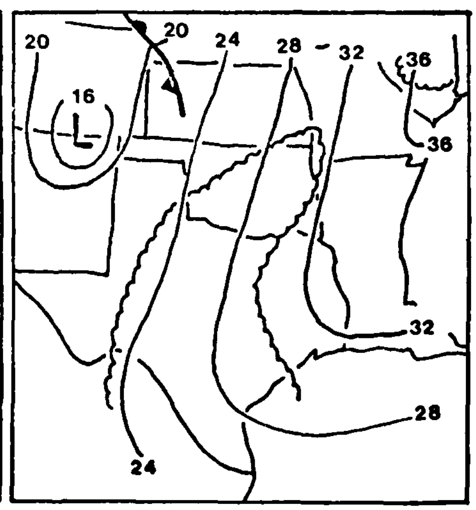
a. 0000 GMT 10 December 1977



b. 1200 GMT 10 December 1977

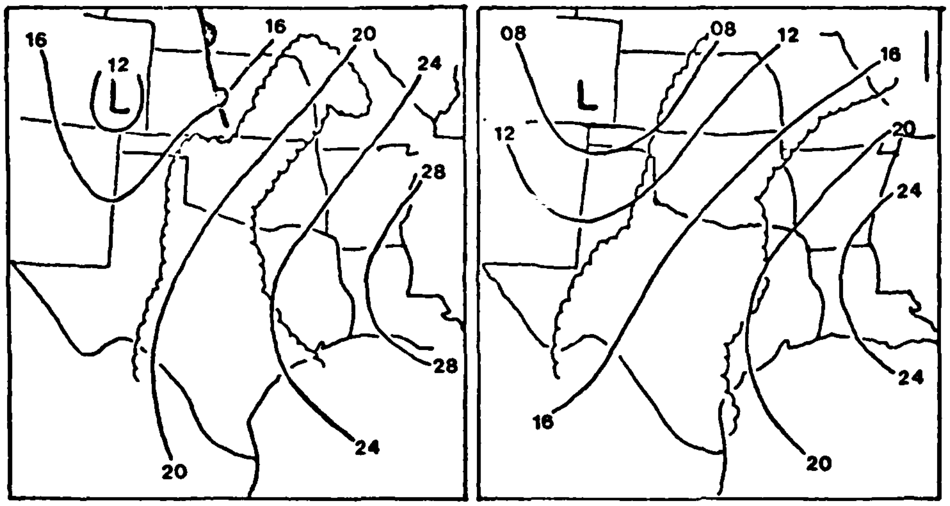


c. 0000 GMT 11 December 1977

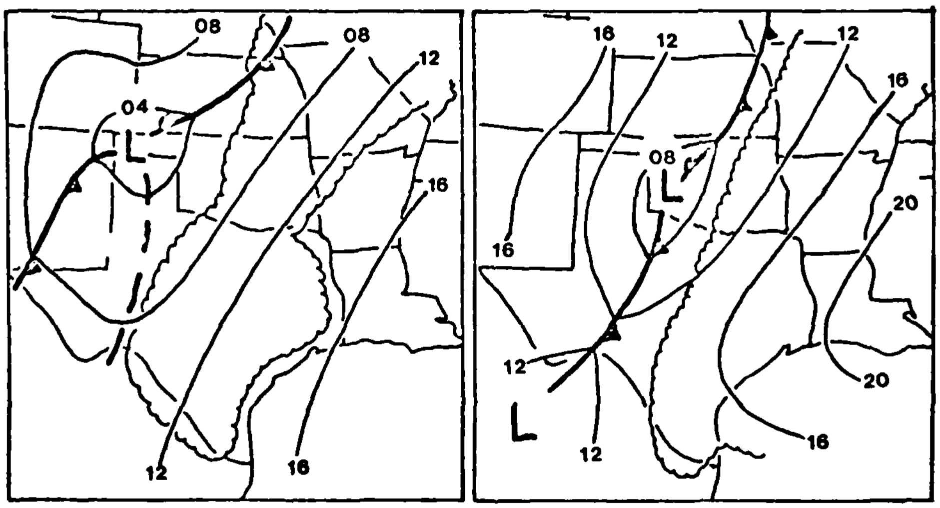


d. 1200 GMT 11 December 1977

Fig. 6. Same as Fig. 1 except for 10-13 December 1977.



e. 0000 GMT 12 December 1977 f. 1200 GMT 12 December 1977



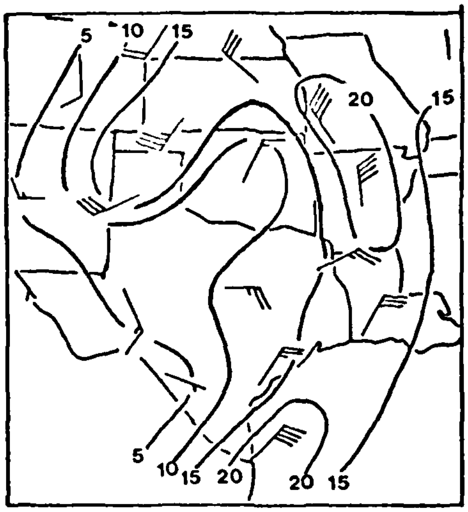
g. 0000 GMT 13 December 1977 h. 1200 GMT 13 December 1977

Fig. 6. Continued.

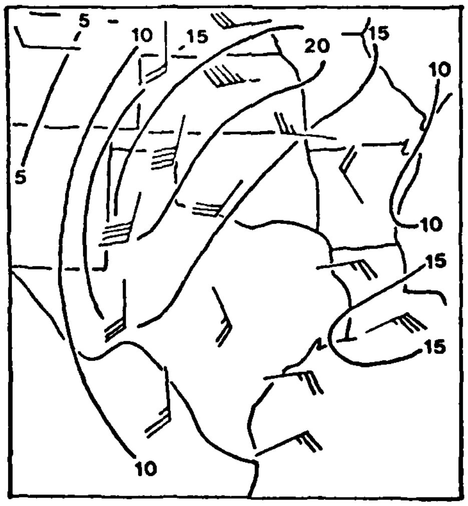
Surface winds on the lee side of the Rocky Mountains were light and southerly. At 850 mb, a high pressure area was centered over northern Texas with southerly flow reaching from Del Rio, Texas, into South Dakota. At 700 mb and 500 mb, flow was northwesterly over the lee side of the Rocky Mountains. Flow became westerly over the area of cyclone development on 11 December 1977. A deep upper-air trough at 700 mb approached the area of cyclone development late on 11 December 1977. At 500 mb, there was weak negative vorticity advection over the region on 10 December 1977, with positive vorticity advection during the remainder of the period.

During the night, pressure fell on the lee side of the Rocky Maintains and by 1200 GMT 10 December 1977, a low developed in northern Colorado (Fig. 6b). During the same time period, both an 850 mb lee trough and a LLJ had developed. Subsequent development of the cyclone is shown in Figs. 6c-h. The development of the LLJ is shown in Figs. 7a-b with the core of the LLJ located over the high plains and extending into central Kansas. Subsequent development and movement of the LLJ is shown in Figs. 7c-f. The southern extension of the LLJ reached the Gulf of Mexico between 1200 GMT 10 December 1977 and 0000 GMT 11 December 1977, coincident with the advection of low-level water vapor, indicated by the expansion of low cloudiness areas into the southern Great Plains.

The cyclone moved to the east on 13 December 1977 and had a minimum central pressure of 1004 mb while in the Great Plains. As the cyclone moved to the east, the LLJ core retained its vertical and horizontal characteristics as it moved in advance of the cyclone.

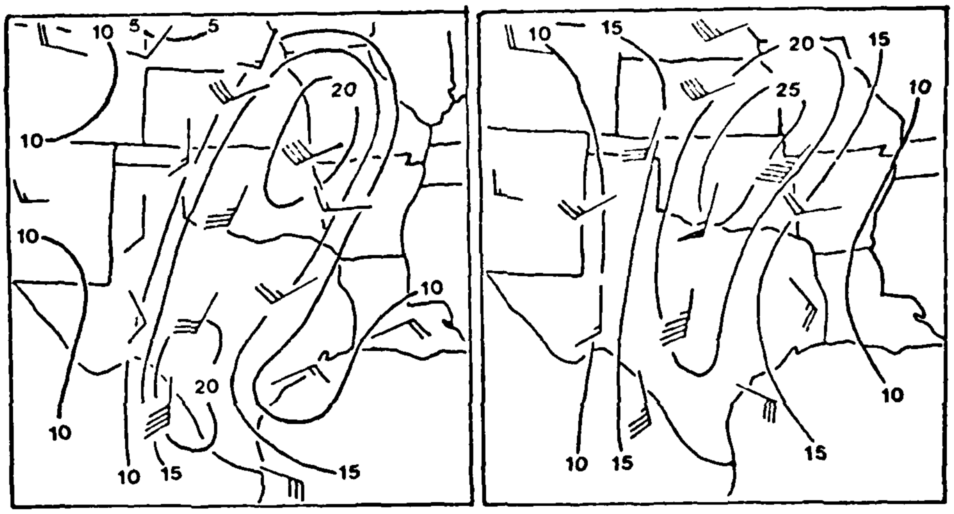


a. 0000 GMT 10 December 1977

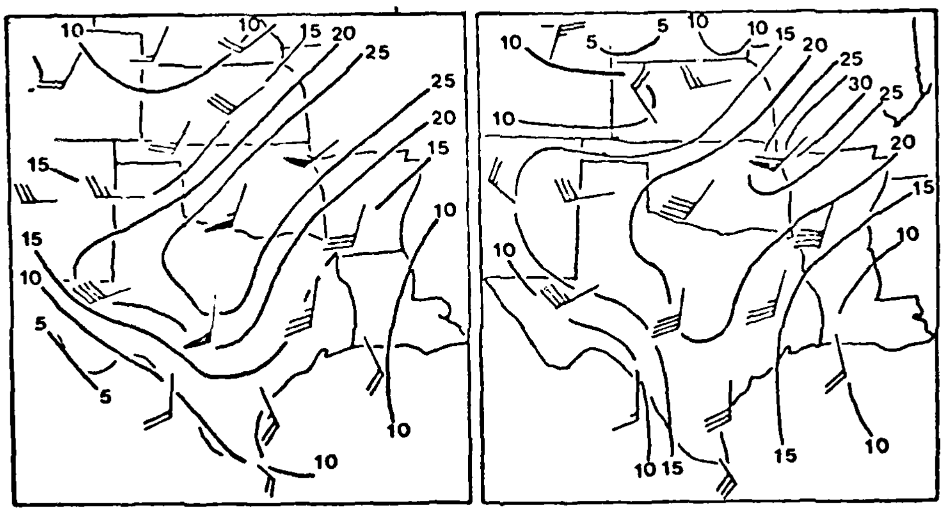


b. 1200 GMT 10 December 1977

Fig. 7. Same as Fig. 3 except for 10-13 December 1977.



c. 0000 GMT 11 December 1977 d. 0000 GMT 12 December 1977



e. 1200 GMT 12 December 1977 f. 0000 GMT 13 December 1977

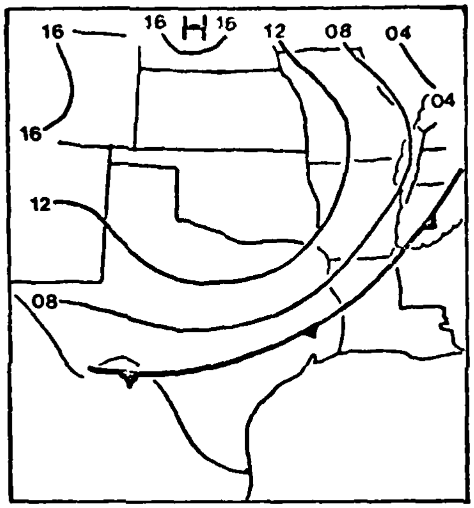
Fig. 7. Continued.

During the period, the LLJ had a maximum observed core speed of 30 m s^{-1}. The LLJ core maintained a continuous height of 1 km above the surface throughout the period and was located within the polar air mass.

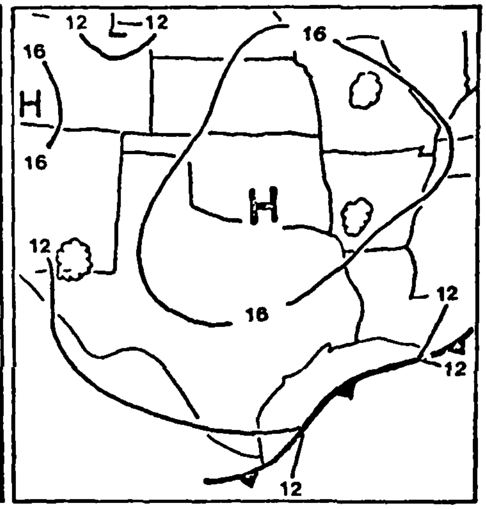
This episode again shows the increase in baroclinity resulting from the advection of warm and moist air brought about by the LLJ during cyclogenesis. This case was the most developed of those cases studied from the winter months of 1977 and 1978.

(4) 9-11 October 1977. In contrast to the previous cases, this case shows the rapid development of a cyclone and associated LLJ and their movement to the east. The rapid development and movement appears to respond to the rapid movement to the east of an upper-level trough. Fig. 8a shows the surface weather situation at 0000 GMT 9 October 1977. A strong cyclone was located over the Great Lakes with a cold front extending into southern Texas. A new cold frontal system was approaching northwestern Colorado while a trough was observed on the lee side of the Rocky Mountains. There was weak southerly flow over the high plains at the surface. Flow at 700 mb and 500 mb was northwesterly over the area of cyclone development. High pressure located over the Texas panhandle at 0000 GMT moved into central Texas by 1200 GMT at which time a low pressure area developed over southern Wyoming. During this time, there was neutral vorticity advection at 500 mb.

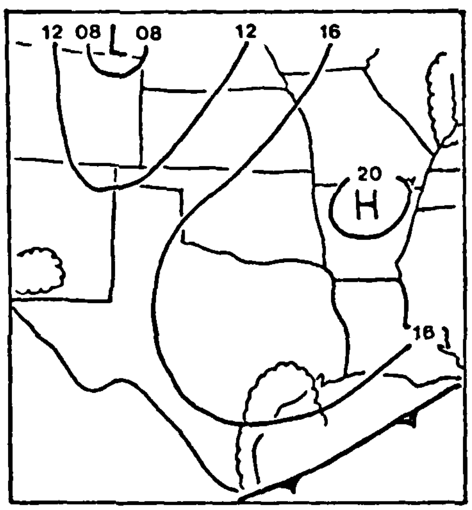
A lee trough continued to develop throughout the day on 9 October 1977 (Fig. 8b-c), and a closed low pressure area was observed in southern Colorado by 0000 GMT 10 October 1977 (Fig. 8d).



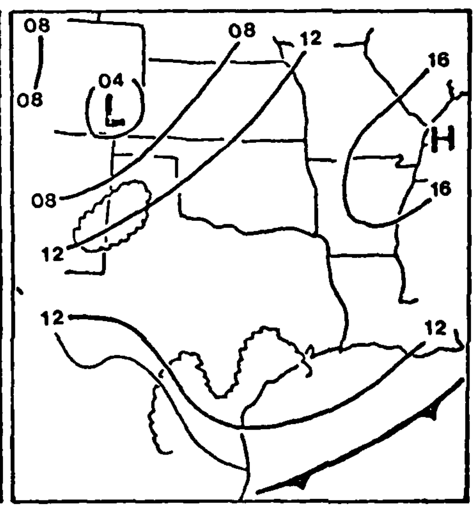
a. 0000 GMT 9 October 1977



b. 1200 GMT 9 October 1977

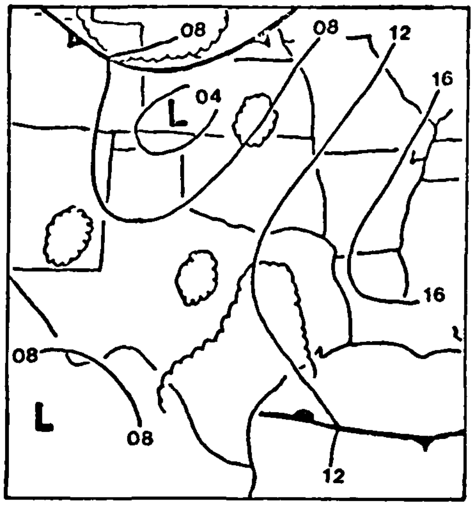


c. 1800 GMT 9 October 1977

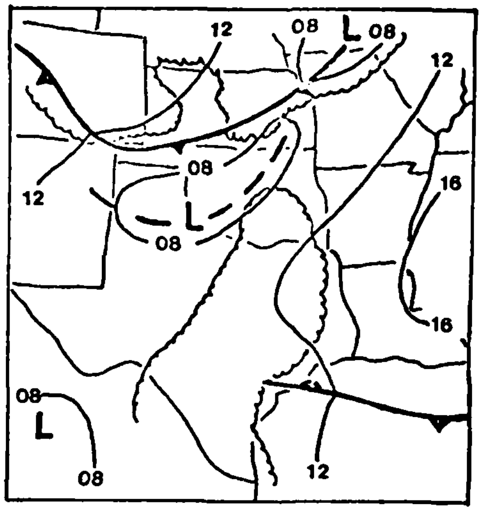


d. 0000 GMT 10 October 1977

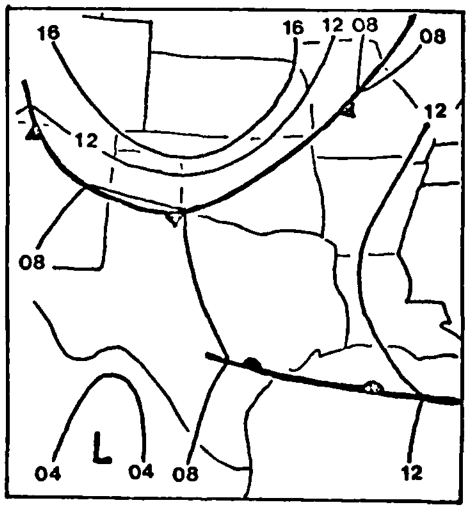
Fig. 8. Same as Fig. 1 except for 9-11 October 1977.



e. 1200 GMT 10 October 1977



f. 1800 GMT 10 October 1977



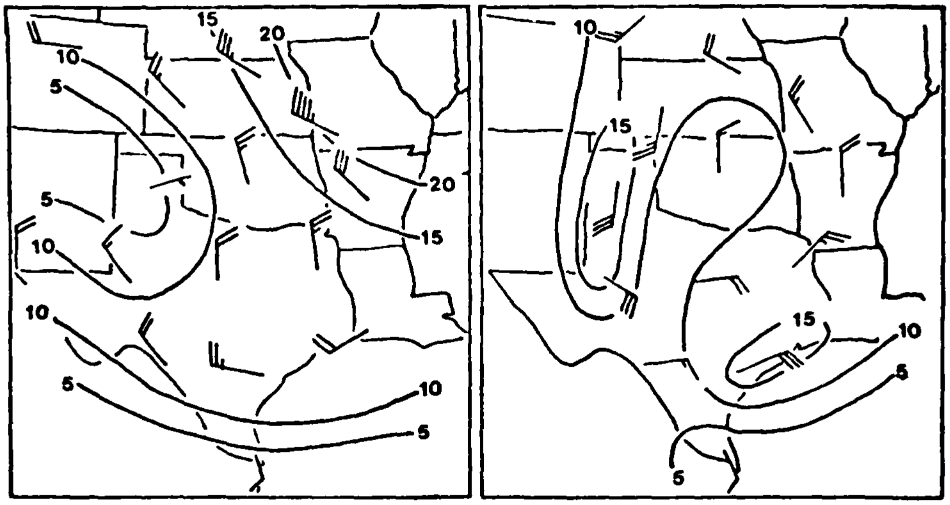
g. 0000 GMT 11 October 1977

Fig. 8. Continued.

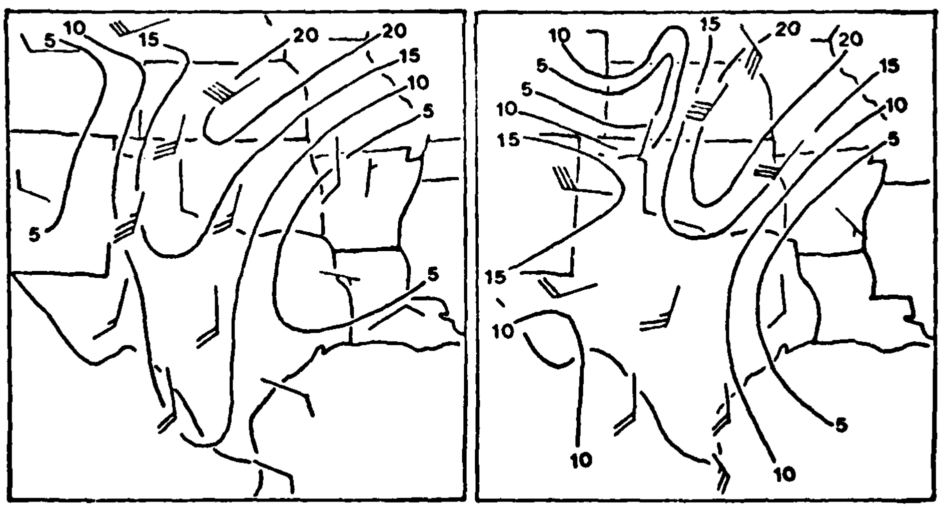
Subsequent development and movement of this low pressure area is shown in Figs. 8e-g. The low which developed in southern Oklahoma filled during the next 6 h as the major low pressure area moved along the front to the northeast (Fig. 8f).

A LLJ developed early on 9 October 1977, and its development and movement is shown in Figs. 9a-d. The southern extension of the LLJ reached the Gulf of Mexico at 0000 GMT 10 October 1977 when areas of low cloudiness expanded into the southern Great Plains. As the cyclone moved to the east, the LLJ moved in advance of the cyclone while maintaining its vertical and horizontal characteristics. The LLJ was observed in the polar air mass at a height of approximately 1 km above the surface. During the period, the LLJ had an observed maximum core speed of 21.5 m s^{-1}.

The simultaneous development of the cyclone and the LLJ is again evident although the definition of each is not as clear as that of previous cases. This may be a result of the rapid movement of the upper-air trough.



a. 0000 GMT 9 October 1977 b. 1200 GMT 9 October 1977



c. 0000 GMT 10 October 1977 d. 1200 GMT 10 October 1977

Fig. 9. Same as Fig. 3 except for 9-10 October 1977.

5. PROPERTIES OF CASES STUDIES

a. Statistics of cases studied

From the two years of data, there were 29 cases where missing or garbled data did not affect the analysis of each of the characteristics shown in Table 1. Three cases are not shown due to missing or garbled data.

Of the 29 cases of cyclone development, 26 (89.6%) had LLJ development. Of these 26 cases, 23 (88.5%) had a "Strong" LLJ, while 3 had a "Weak" LLJ (11.5%).

There was very little difference between the average initial and the lowest central cyclone pressure with respect to the strength of the LLJ. It was noted, however, that the lowest central cyclone pressure was observed in cases where there was a strong LLJ.

At the time of the initial low pressure development on the lee side of the Rocky Mountains, northwesterly to westerly flow was observed in 80.8% of the 26 cases in which there was LLJ development. This indicates that the initial development of the cyclone is probably dependent on the adiabatic warming associated with zonal flow aloft on the lee side of the Rocky Mountains.

Of the 29 cases, 76% had advection of low-level water vapor indicated by a moist tongue in a surface isodrosotherm analysis or the observed expansion of areas of low cloudiness. In 10% of the cases, there was low cloudiness that remained in the region after passage of a previous cold frontal system. In 23 of the 26 cases in which there was LLJ advection of low-level water vapor, there was an average difference in initial and lowest central cyclone pressure of 8.28 mb. This difference was only 2.5 mb for those cases in which there was no LLJ advection of low-level water vapor. This finding supports the concept of enhanced cyclone development in the presence of advection of low-level water vapor.

Three cases were noted in which no LLJ developed. In these cases, pressure fall during cyclogenesis was less than 5 mb, and there was no indication of an inversion in the lowest 2 km of the atmosphere. These two characteristics were much more apparent in the other 26 cases where there was simultaneous cyclone and LLJ development.

b. Individual case studies

In each of the cases studied, there were many similar characteristics. As lows developed on the lee side of the Rocky Mountains, there was subsequent development of a LLJ over the high plains. The development pattern was similar to that described by Djurić and Damiani (1980); therefore, the development pattern from that report using the stages of "A" through "D" is used in this study with the addition of Stage A'. In Stage A, northerly wind was observed over the high plains at the level of the maximum wind in the lower troposphere. During Stage A' (Fig. 10a), the LLJ begins to form over the High Plains as a result of an isallobaric wind which is initiated by pressure fall on the lee side of the Rocky Mountains. During the next 12 h, the wind adjusts geostrophically over the high plains. The wind now appears to be representative of a LLJ and the development

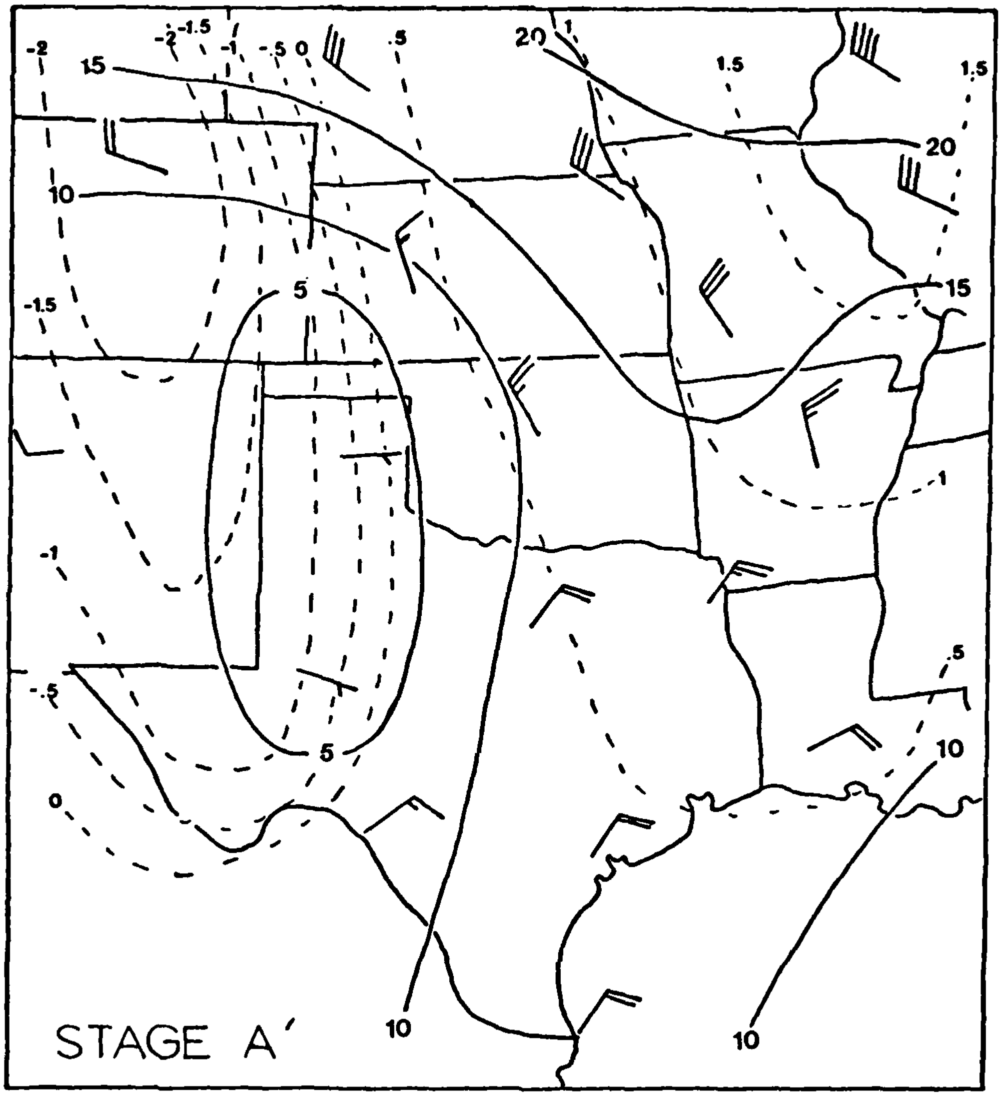


Fig. 10a. A schematic representation of the wind at the level of the maximum wind in the lowest 2 km of the atmosphere with isotach analysis (m s^{-1}). Each barb represents 5 m s^{-1}. Dashed lines represent isallobars (mb (3 h)$^{-1}$).

is categorized as Stage B (Fig. 10b). This development pattern seems to confirm the hypothesis presented in Section 2 of this paper. During Stage B, there was a strong gradient of isallobars in central Oklahoma and Texas. An isallobaric wind appears to develop in this area in response to the pressure fall.

The geostrophic adjustment of the initial isallobaric wind merits a more detailed description. As a katallobaric axis approaches the station, wind at the level of the maximum wind in the lowest 2 km of the atmosphere acquires an isallobaric component from the east. As the axis passes over the station, the gradient reverses, and the wind has an isallobaric component directed from the west. Due to inertia, the wind blows from the east but is decreased by this reversed isallobaric component. Also, as the katallobaric axis continues to move to the east past the station, the wind over the station responds to the increasing pressure gradient from the developing cyclone on the lee side of the Rocky Mountains. This, combined with coriolis effects, brings about the geostrophic adjusted flow.

By Stage C (Fig. 10c), southerly wind at the LLJ core level spreads into Oklahoma and Texas, and the wind at the level of the maximum wind in the lowest 2 km of the atmosphere appears to have become geostrophically adjusted in these areas. The LLJ core remained over western Texas, Oklahoma, and Kansas during this time. As the cyclone continued to intensify, the LLJ development could be categorized as Stage D (Fig. 10d). At this time the core of the LLJ moved to a position over the central Great Plains.

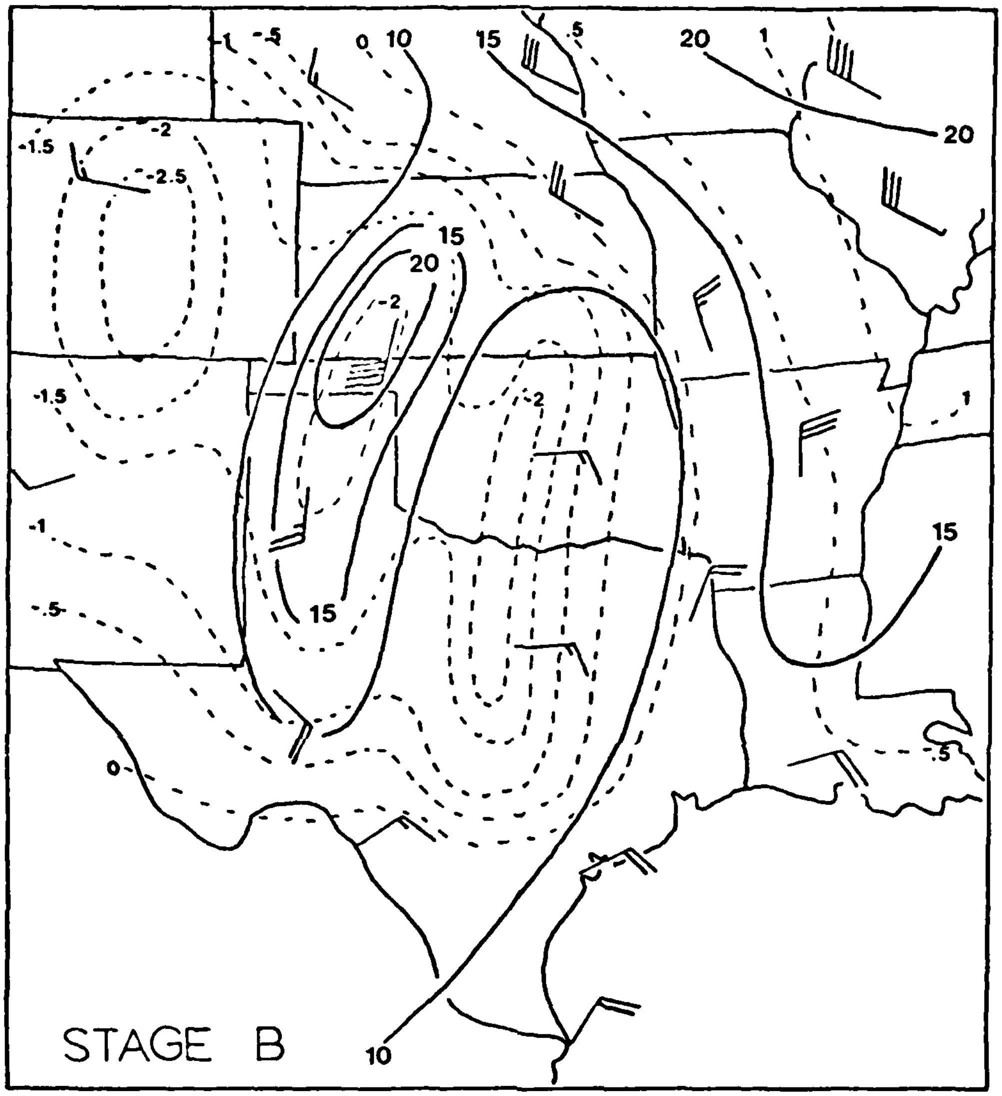


Fig. 10b. Same as Fig. 10a except for Stage B.

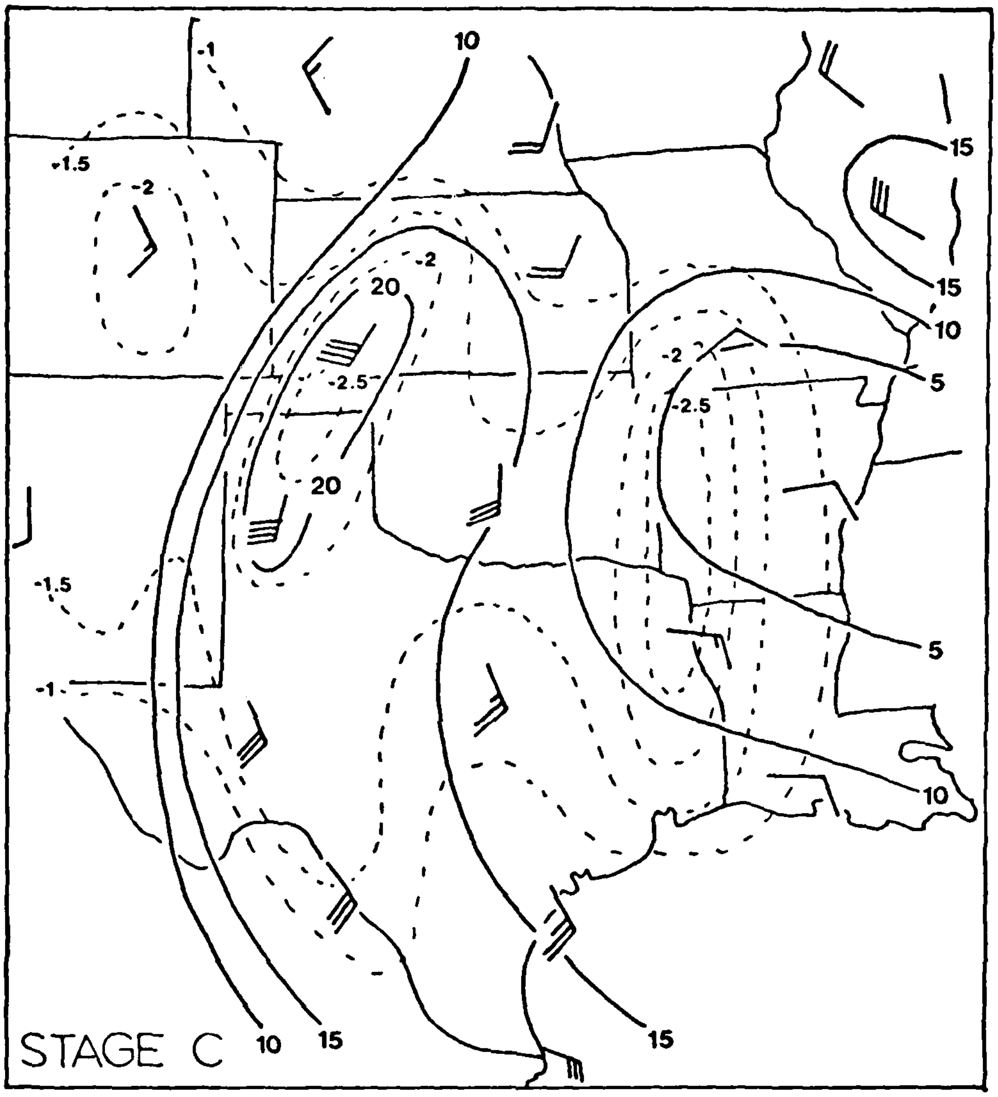


Fig. 10c. Same as Fig. 10a except for Stage C.

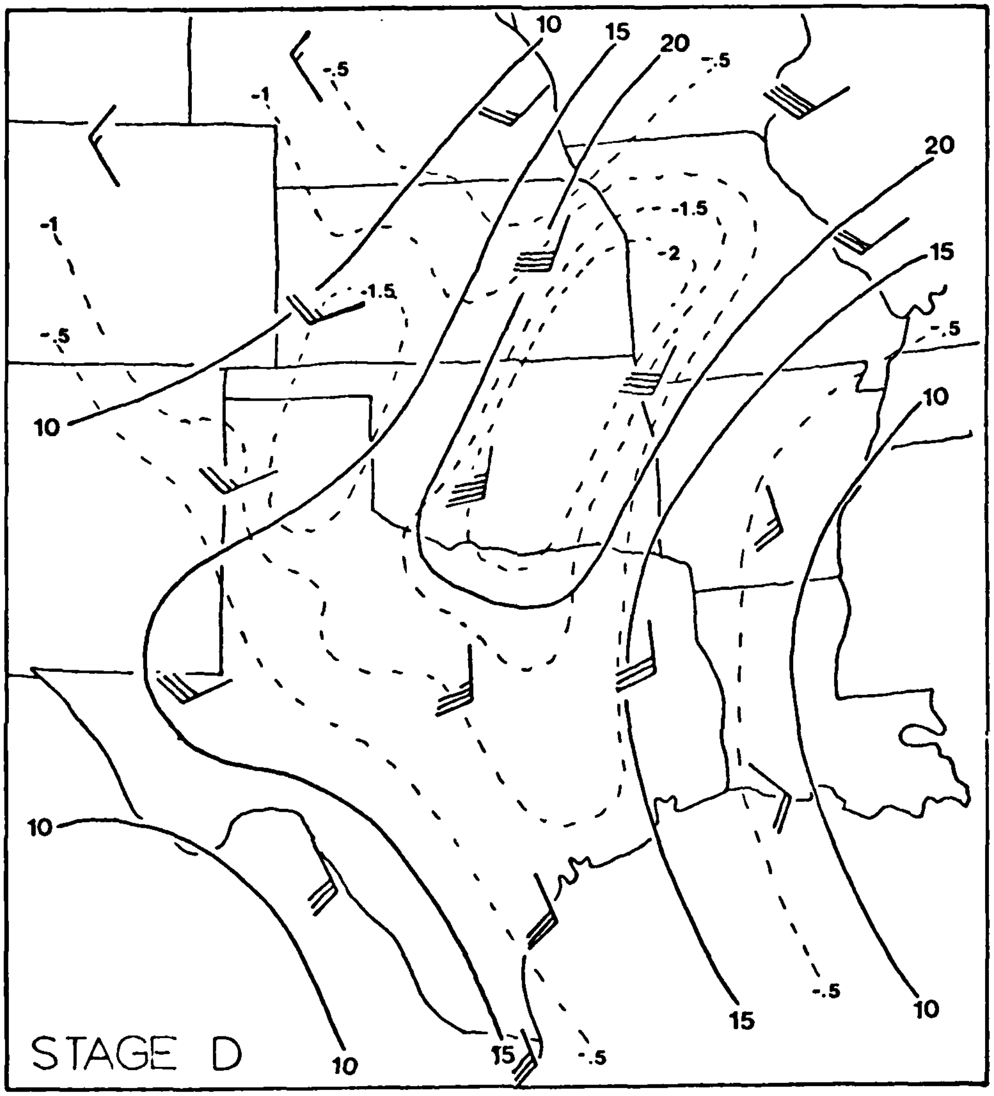


Fig. 10d. Same as Fig. 10a except for Stage D.

A somewhat different LLJ development pattern appeared in the case of 10-13 December 1977. In this case, Stage A' did not appear, and the first appearance of the LLJ coincided with Stage B (Fig. 11). The remainder of the developmental process proceded as described earlier. The difference in the developmental process appears to be dependent on the position of the anticyclone over the Great Plains. A high pressure area was centered in northern Texas at 850 mb, and strong return flow on the western side of the anticyclone was apparent not only over the high plains, but in southern Texas.

The expansion of areas of observed low-level cloudiness was used as an indication of the movement of water vapor into the southern Great Plains. In three of the cases, the areas of observed low-level cloudiness expanded from the Texas Gulf coast into the southern Great Plains. The effect of LLJ advection of low-level water vapor could be seen better through the use of a surface isodrosothermic analysis. The location and development of the moist tongue closely paralleled the location and development of the LLJ as the LLJ core moved through the Great Plains. Using the case of 10-13 December 1977 as an example, the core of the LLJ moved into the southern Great Plains at 0000 GMT 12 December 1977 (Fig. 12a). An isodrosotherm analysis at the surface and the observed low cloudiness is shown in Fig. 12b. The low cloudiness was observed below the level of the LLJ core. Both the axis of the moist tongue at the surface and the areas of observed low cloudiness are displaced to the left of the core of the LLJ. This may be due to either a secondary circulation in the Ekman layer imposed by the LLJ or the trajectory of parcels which were in

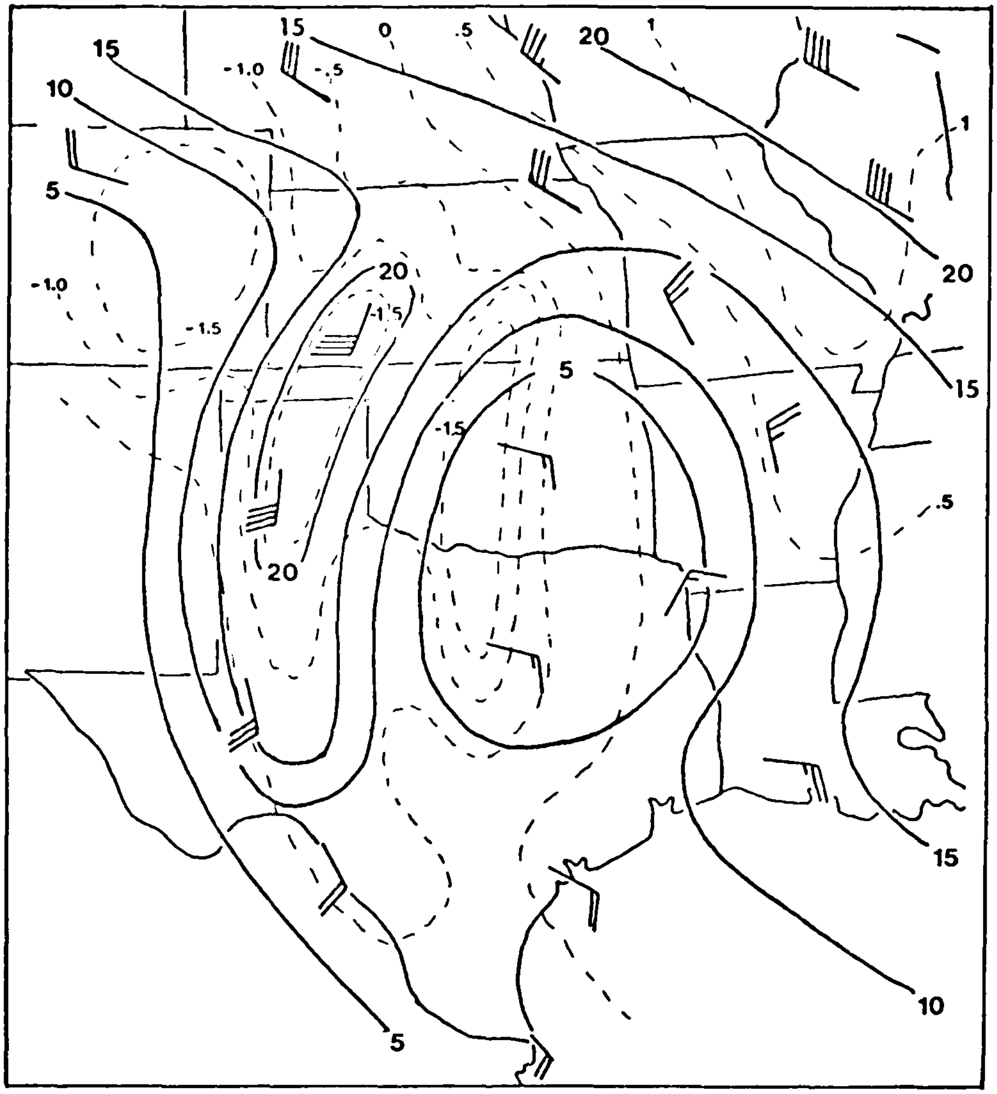
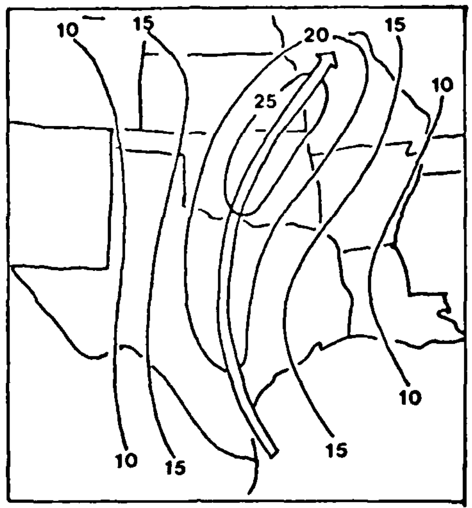
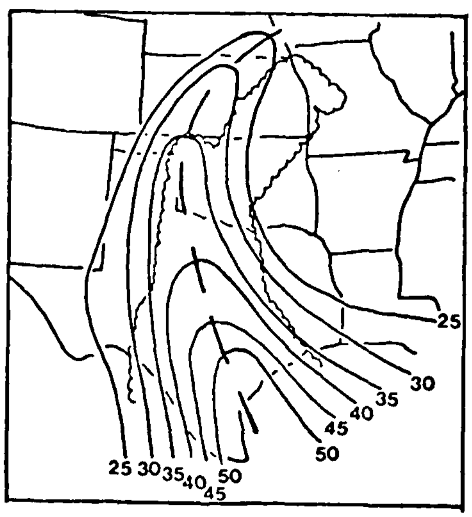


Fig. 11. Same as Fig. 10a except for the case of 10-13 December 1977 and corresponding to Stage B at 0000 GMT 10 December 1977.



a. LLJ core position with isotachs (m s^{-1})

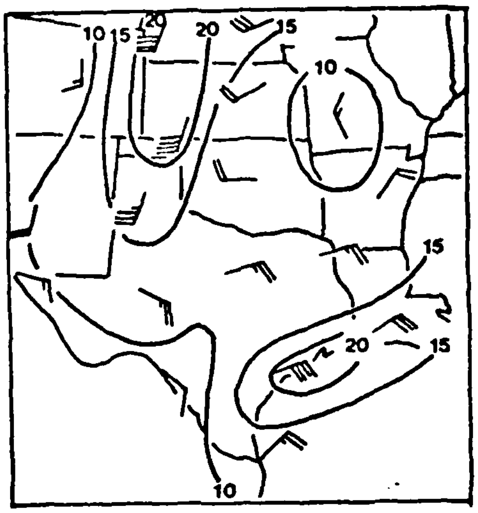


b. Surface isodrosothermic analysis (^{o}F) with low cloudiness designated within scalloped area

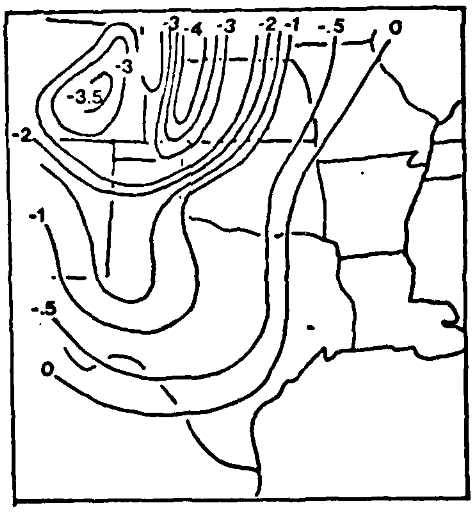
Fig. 12. Comparison of LLJ core position to surface moist tongue and areas of low cloudiness at 0000 GMT 12 December 1977. Double arrow represents LLJ core. Heavy dashed line represents axis of surface moist tongue.

the LLJ during a previous time period. This characteristic was evident in each of the other cases studied. In each, the advection of low-level water vapor into the southern Great Plains occurred when the southern extension of the LLJ reached the northern Gulf of Mexico.

A marked pattern appears in the isallobaric field beneath the LLJ core in each case. Three-hourly pressure tendency, analyzed at the surface at upper-air sounding times, shows that as the LLJ develops, an axis of maximum pressure fall is observed at the surface below the LLJ core. Using the case of 17-20 December 1978 as an example, Fig. 13a shows the initial development of the LLJ, and Fig. 13b shows the surface isallobaric pattern at 1200 GMT 17 December 1978. One maximum of pressure fall corresponds to the position of the LLJ core, while another axis corresponds to the region of pressure fall associated with the developing cyclone in southern Colorado. The high wind speed located over southeastern Texas showed no LLJ characteristics, and there was no notable isallobaric feature in this area. During the next 12 h, the LLJ core rotated to a southwest-to-northeast orientation (Fig. 14a). Again, there is a maximum of pressure fall at the surface beneath the LLJ core in western Kansas (Fig. 14b). The relative maximum of pressure fall in Oklahoma corresponds to the edge of the horizontally spreading southerly wind at the level of the LLJ core. By 1200 GMT 18 December 1978, the LLJ core moved into central Oklahoma (Fig. 15a). Again, an axis of maximum pressure fall corresponded closely with the position of the LLJ core (Fig. 15b).

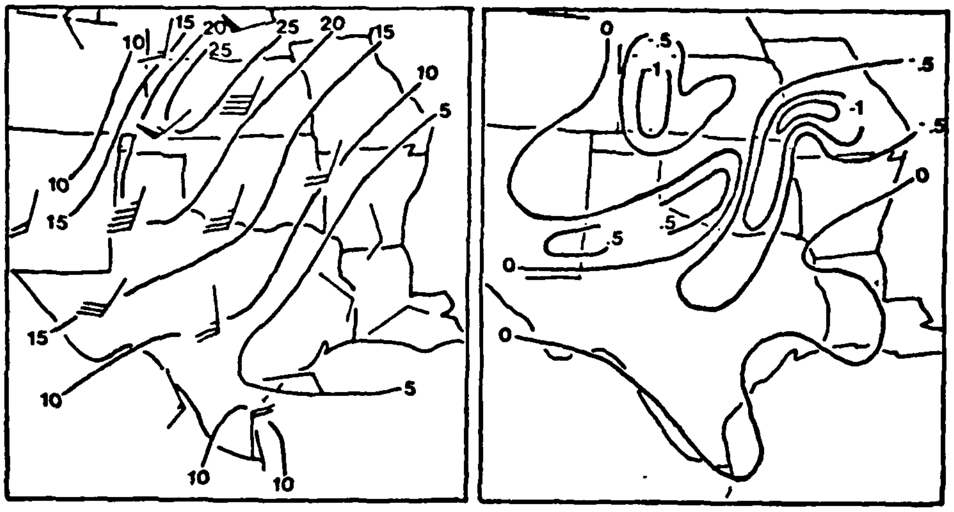


a. Winds at the level of the maximum wind



b. Surface isallobaric pattern

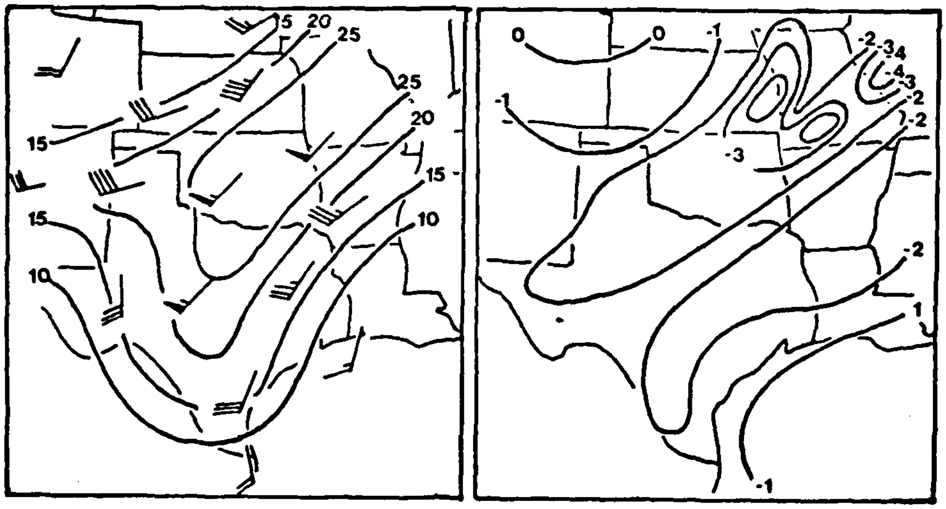
Fig. 13. Comparison of the winds at the level of the maximum wind in the lowest 2 km of the atmosphere with the surface isallobaric pattern at 1200 GMT 17 December 1978. Isotachs are analyzed at 5 m s^{-1} intervals and isallobars are analyzed at 0.5 mb (3 h)$^{-1}$ intervals.



a. Winds at the level of the maximum wind

b. Surface isallobaric pattern

Fig. 14. Same as Fig. 13 except for 0000 GMT 18 December 1978.



a. Winds at the level of the maximum wind

b. Surface isallobaric pattern

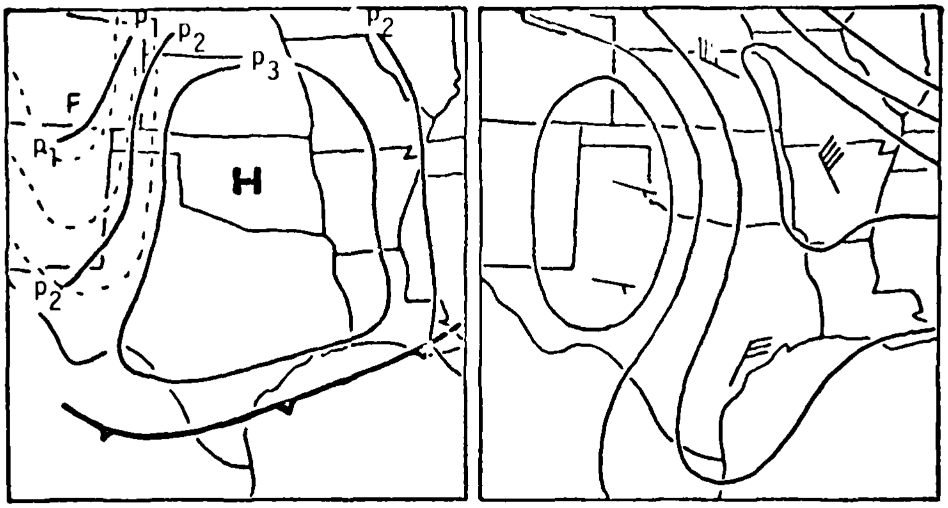
Fig. 15. Same as Fig. 13 except for 1200 GMT 18 December 1978.

6. MODELS

a. The descriptive model

Based upon the results of both the data tabulation of all cases and the study of individual cases, a model is presented which shows the simultaneous development of the cyclone on the lee side of the Rocky Mountains and its associated LLJ. Figs. 16-20 show the development of the cyclone and LLJ in 12 h steps. The final step shown in Fig. 20 is that of the fully developed cyclone moving through the Great Plains and described in Newton's (1967) model. This model incorporates those characteristics found in nearly every case of cyclogenesis during the period of this study.

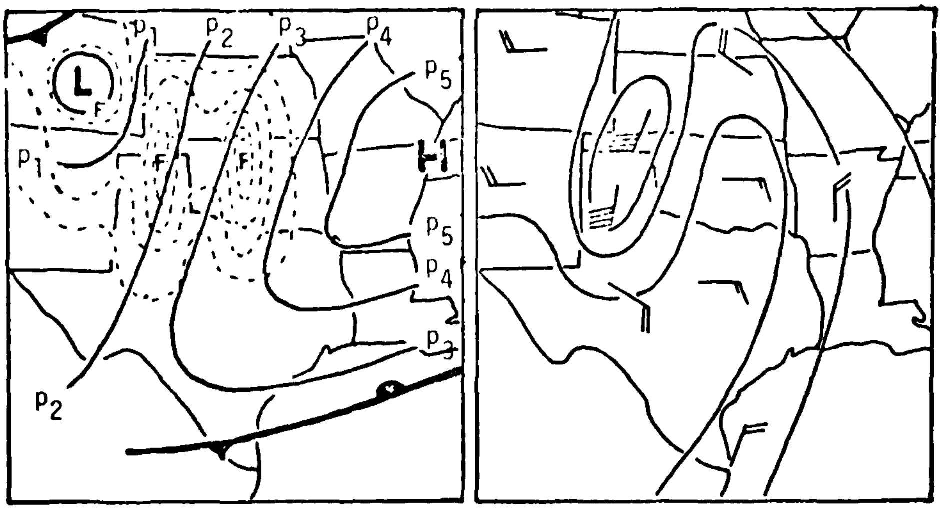
Initially, a polar air mass of either maritime or continental origin moves into the southern Great Plains. The high pressure area may continue to move southward toward the Gulf of Mexico or move northeastward (Fig. 16a). There is no indication of a southerly wind maximum at the level of the maximum wind in the lowest 2 km (Fig. 16b), although weak southerly flow may be present at the surface over the high plains. At this time, pressure falls are observed on the lee side of the Rocky Mountains. During the next 12 h, a low pressure area developed on the lee side of the Rocky Mountains (Fig. 17a). A cold frontal system may approach from the northwest during this stage. As pressure continued to fall on the lee side of the Rocky Mountains while a second katallobaric center was observed over the High Plains. This axis corresponds to the position of the developing LLJ core (Fig. 17b). Another axis of maximum pressure fall



a. Surface analysis

b. Winds at the level of the maximum wind

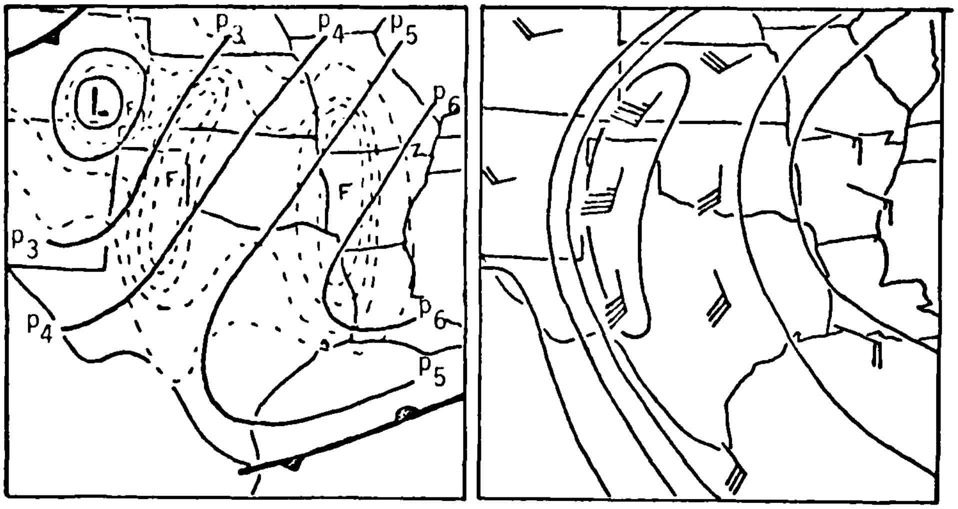
Fig. 16. Model depicting cyclone and LLJ development. Solid lines represent isobars and dashed lines represent isallobars. Isotachs are in 5 m s^{-1}. "F" denotes pressure fall areas (mb (3 h)$^{-1}$).



a. Surface analysis

b. Winds at the level of the maximum wind

Fig. 17. Same as Fig. 16 except for 12 h later.



a. Surface analysis

b. Winds at the level of the maximum wind

Fig. 18. Same as Fig. 16 except for 24 h later.

a. Surface analysis

b. Winds at the level of the maximum wind

Fig. 19. Same as Fig. 16 except for 36 h later.

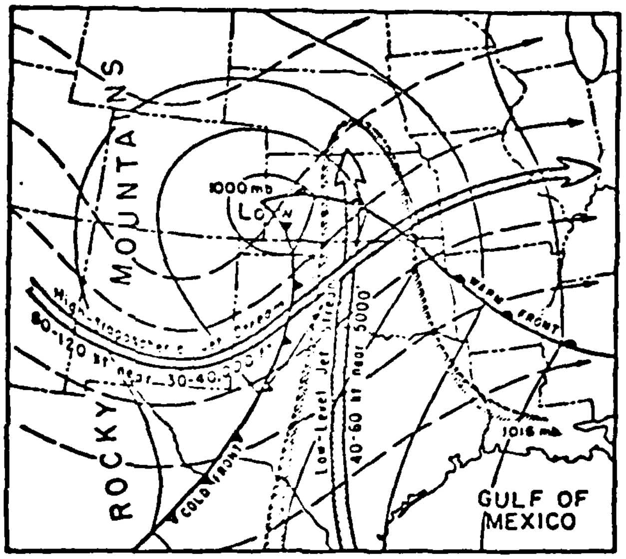


Fig. 20. Newton's (1967) model of a cyclone moving through the Great Plains.

may be found in the central Great Plains. Normally no advection of low-level water vapor is observed at this time. Since flow is normally westerly to northwesterly in the mid- and upper-troposphere over the area of cyclone development, adiabatic warming resulting from the zonal-to-northwesterly flow aloft is the probable cause of pressure fall on the lee side of the Rocky Mountains.

During the next 12 h the low pressure area on the lee side of the Rocky Mountains deepened. Mid- and upper-tropospheric flow may become southwesterly indicating the approach of the mid- and upper-level trough (Fig. 18a). Also, the cold frontal system advances from the northwest closer to the lee side of the Rocky Mountains. Three principal katallobaric centers are now present. One corresponds to the region of low pressure development. Another appears below the LLJ core, and a third appears near the eastern edge of the area of southerly wind at the level of the LLJ core (Fig. 18b). At this time, LLJ advection of water vapor may be noted if the southern extension of the LLJ reaches an area over the northern Gulf of Mexico.

During the final 12 h leading to the time shown in Newton's (1967) model, the upper-tropospheric trough approaches the area of cyclone development. The low pressure area has now become a wave on the front, and pressure falls are noted to the right of the cyclone (Fig. 19a). The same katallobaric pattern noted previously is observed beneath the position of the LLJ core (Fig. 19b). The expansion of areas of low-level cloudiness and increasing dew-point temperature is now present well into the southern Great Plains. The axis of the moist tongue at the surface and cloudiness observed below the height of the LLJ core are displaced somewhat to the left of the position of the LLJ core. Fig 20 shows the development time presented in Newton's (1967) model.

b. Low-level jet origin

Data from the two winters suggests that, although there was weak return flow on the western side of the anticyclones over the Great Plains which may be a contributing factor to the development of the LLJ, a second, and possibly more important, factor exists. This explanation can be found in the results of the isobaric and isallobaric analysis done in this study and confirms the hypothesis of LLJ development resulting from pressure fall during cyclogenesis presented earlier in this paper.

During the early period of LLJ development, light easterly winds may be observed over the high plains at the elevation at which the LLJ later forms. Later in the episode, this same observation is noted over the central Great Plains after the LLJ has developed over the high plains. At this time, there is an axis of maximum pressure fall at the surface beneath both the LLJ core and the horizontal edge of the spreading southerly wind at LLJ core level. This isallobaric pattern suggests that the development of the LLJ may be due to the isallobaric wind which develops in response to pressure falls on the lee side of the Rocky Mountains. This isallobaric wind gradually adjusts and becomes geostrophic. As this geostrophic adjustment process takes place, the wind turns from an easterly direction to a southerly direction.

This development process is shown schematically using the five stage approach described by Djurić and Damiani (1980) in a cross-section at a latitude of 36° North (Fig. 21). During Stage A, a polar high pressure area moved into the southern Great Plains. At this time, an arbitrary constant pressure surface above the surface and within or below an inversion is smooth and sloped downward to the right to account for the northerly wind observed over the Great Plains. Between Stages A and B (Stage A'), isallobaric wind resulting from pressure fall on the lee side of the Rocky Mountains may be apparent at the level where the LLJ is later observed. In Stage B, a weak southerly LLJ is observed over the high plains centered on the steep slope of the constant pressure surface while a perturbation on the constant pressure surface moves to the east into Oklahoma. During Stage C, the southerly LLJ continues to strengthen due to the increasing pressure gradient brought about by the developing cyclone. The perturbation continues to move to the east with the approximate speed of a gravity-inertia wave. As the perturbation approaches a station, the wind at the level of the maximum wind in the lowest 2 km over the station acquires an isallobaric component. A geostrophically adjusted wind can only be found at some time after the perturbation has passed over a specific station. While the perturbation is moving to the east, pressure continues to fall on the lee side of the Rocky Mountains, and the LLJ continues to strengthen. This continuing pressure fall may be in response to either continued adiabatic warming resulting from zonal flow aloft, or to the approach of an upper-tropospheric trough. In Stage D, the LLJ core moves to the

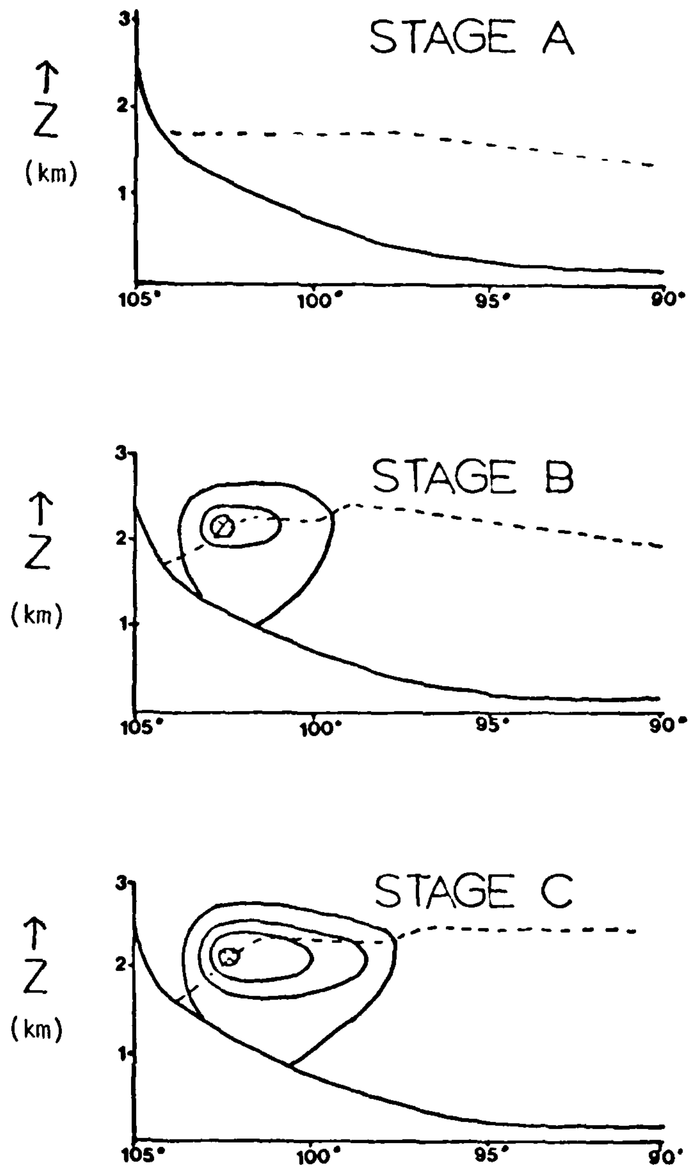
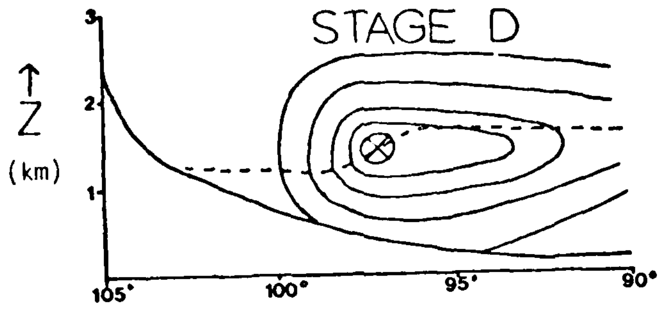


Fig. 21. Development and movement of the LLJ. The cross-section is at a latitude of 36° N. Dashed lines represent an arbitrary constant pressure surface. Solid lines represent isotachs. The abscissa is in degrees longitude. "Z" represents height.



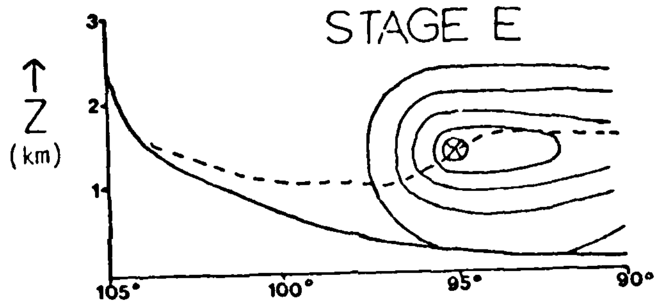


Fig. 21. Continued.

east into the central Great Plains. The low pressure area in Colorado becomes a frontal cyclone, and, during Stage E, begins to move to the east. At this time, the constant pressure surface over the lee side of the Rocky Mountains begins to rise, and the wind becomes westerly to northwesterly over the High Plains.

The description given above offers a possible explanation of the development of the LLJ during the development of a cyclone. The geostrophic adjustment of initially isallobaric wind developing as a result of pressure fall on the lee side of the Rocky Mountains may account for the appearance of strong LLJs in this area.

c. Computations using models

Computed height fall patterns at an arbitrary level within the layer in which the LLJ is observed correspond closely to the observed surface pressure tendency patterns. The correlation between these patterns seems to verify that axes of maximum pressure fall at the surface are observed beneath the core of the LLJ. Using the numerical model designed by Djurić (1980), height falls were computed on a constant pressure surface within the layer in which a LLJ is observed. This computation was then compared to the LLJ core position and the position of katallobaric axes at the surface. The calculations were made on an axis extending from Dodge City, Kansas (DDC) to Victoria, Texas (VCT). Data for the initialization of the model came from the case at 0000 GMT 19 November 1977. A short alteration was made in the program used for the model so that the computation of height falls could be printed out. Surface pressure falls were converted to height falls using the hydrostatic equation differentiated with respect to time. A comparison of the observed wind at the level of the maximum wind and the computed and observed height fall is shown in Fig. 22. At this time, the southern extension of the LLJ is over Stephenville, Texas (SEP). The LLJ core has not yet reached VCT, but is spreading in that direction. The observed peak wind speed over GAG corresponds to a westerly jet somewhat higher in altitude than the southerly jet over SEP. Observed height fall closely corresponds, as stated previously, to the position of the LLJ and the edge of the horizontally spreading southerly wind. The computed height fall from the model appears to simulate and verify the occurrence of axes of relative maximum height (or pressure) fall beneath the LLJ core and the horizontally spreading edge of the southerly wind at the LLJ core height.

An expansion of Fig. 14b is shown in Fig. 23. In the surface isallobaric analysis at 0000 GMT 18 December 1978, a wave pattern appeared at the surface. This same pattern appeared in some of the other cases studied. The observation of a wave pattern closely parallels the findings of the models of Tepper (1955) and Djuric (1980). Tepper showed that through the addition of momentum to a stream, pressure-jump lines developed and propagated to the right of the stream. A similar pattern is apparent in this case (Fig. 23). As the LLJ increases in strength, a wave pattern appears to develop and may result from the increasing strength of the jet. Although these perturbations are not true pressure-jump lines, some mechanism is present which produces the pressure fluctuations which subsequently

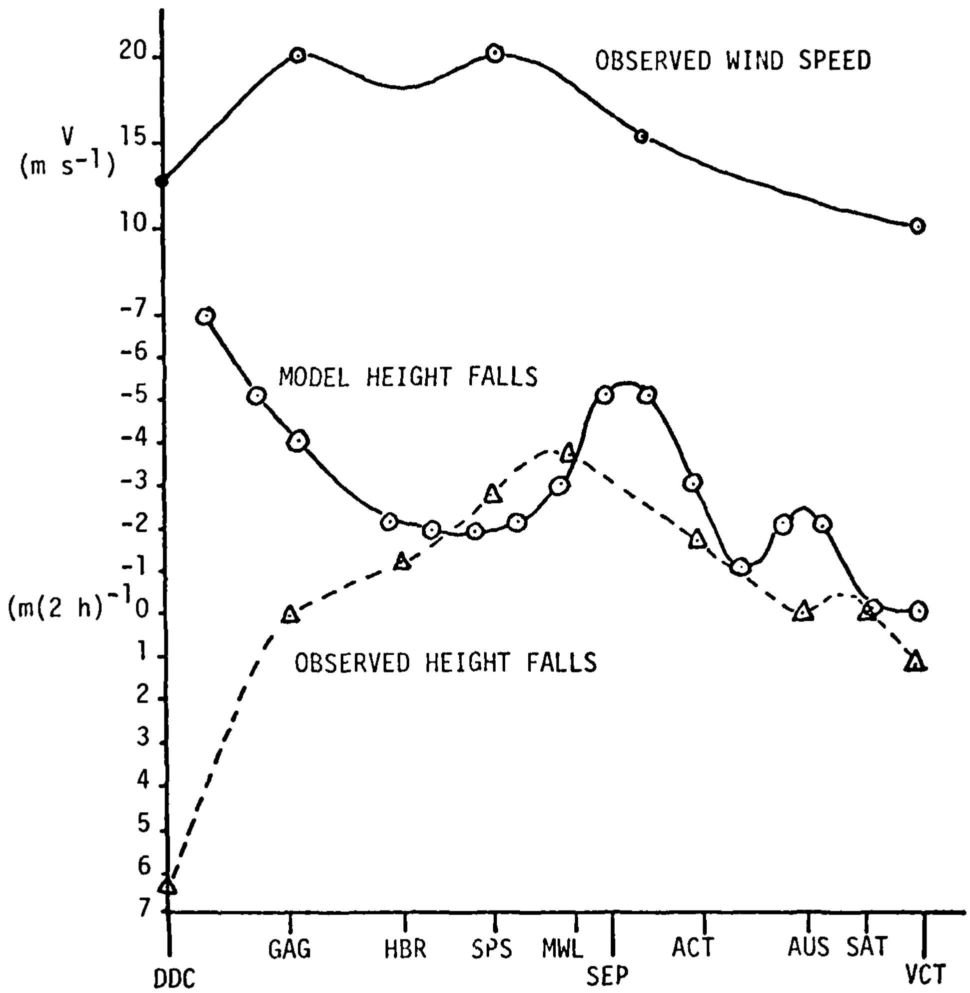


Fig. 22. Comparison of the computed and observed height falls to the observed winds at the level of the maximum wind at 0000 GMT 19 November 1977. Height falls are measured in m (2 h)$^{-1}$. Standard station identifiers are used on the abscissa.

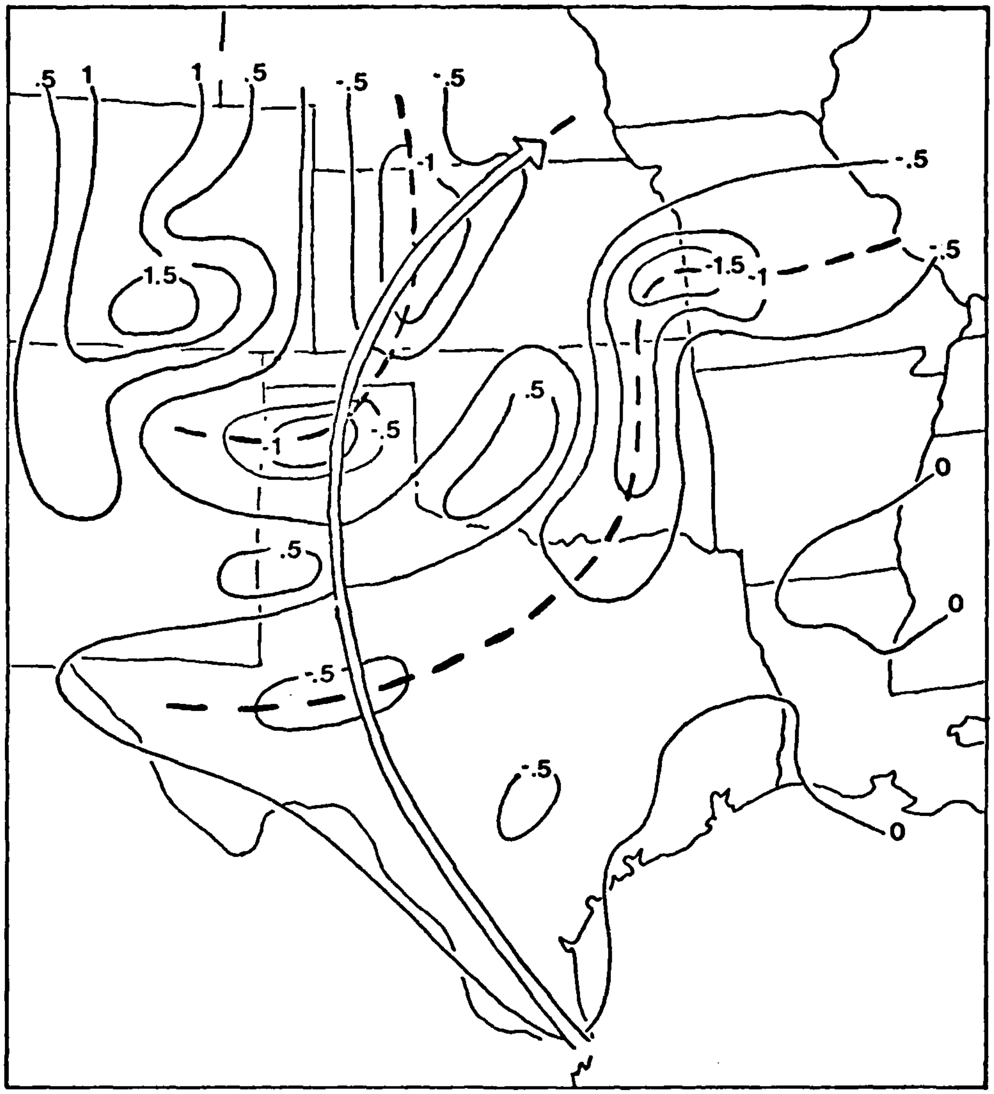


Fig. 23. Surface isallobaric pattern at 0000 GMT 18 December 1978. Solid lines represent isallobars (mb $(3\ h)^{-1}$). Dashed lines represent axes of relative maximum pressure fall. Heavy arrow represents the LLJ core position.

propagate to the east. Djurić (1980) also found this type of wave pattern in calculations made by his model. He found that these perturbations or waves propagate to the east with the approximate speed of a gravity-inertia wave. Although no thunderstorms occurred in this case, the initiation of the wave pattern as the LLJ strengthens could be important in the study of the initiation of convective activity.

7. CONCLUSIONS

Based upon statistics and the study of individual cases from the winter months of 1977 and 1978, a descriptive model is presented which emphasizes the simultaneous development of the winter extra-tropical cyclone and associated LLJ. Further, the importance of the LLJ in the transport of latent heat into the Great Plains, thus enhancing the development of the cyclone as it moves through the Great Plains, is shown.

Evidence is presented that suggests that an explanation of the cause of the LLJ is the gradual geostrophic adjustment of initially isallobaric wind. The isallobaric wind is initiated as a result of pressure fall on the lee side of the Rocky Mountains. The LLJ that develops is located in a layer beneath a frontal or subsidence inversion normally within 2 km of the surface. In the cases studied in this paper, the LLJ was found only in the polar air mass.

The position of the LLJ can be identified in a surface isallobaric analysis. The use of pressure tendency to locate the position of the LLJ core offers an accurate method that can be used between upper-air radiosonde sounding times. This method of locating the position of the LLJ is more accurate than the identification surface moist tongue position and its correlation with the LLJ position.

REFERENCES

Beckman, S. K., 1973: A study of wind speed maxima near the surface over the south central United States. M. S. Thesis. Dept. Meteor., Texas A&M University, 73 pp.

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

Cahn, A., 1945: An investigation of the free oscillations of a simple current system. J. Meteor., 2, 135-162.

Damiani, M. S., Jr., 1979: Structure of the low-level jet over Texas. M. S. Thesis. Dept. Meteor., Texas A&M University, 97 pp.

Djuric, D., 1980: A numerical model of the formation and evolution of a low-level jet. Mon. Wea. Rev. (In press).

Djuric, D., and M. S. Damiani, Jr., 1980: On the formation of the low-level jet over Texas. Mon. Wea. Rev. (In press).

Henry, W. K., 1979: An arbitrary method of separating tropical air from "Return Flow" polar air. Nat. Wea. Dig., 4, No. 4, 22-26.

Henry, W. K., and A. H. Thompson, 1976: An example of polar air modification over the Gulf of Mexico. Mon. Wea. Rev., 104, 1324-1327.

Holton, J. R., 1967: The diurnal boundary layer wind oscillation above sloping terrain. Tellus, 19, 199-205.

Karnavas, G. R., 1978: On polar air modification over the Gulf of Mexico during periods of return flow and development of clouds. M. S. Thesis. Dept. Meteor., Texas A&M University, 69 pp.

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

__________, 1967: Severe convective storms. Advances in Geophysics, 12, Academic Press, 257-303.

Obukhov, A., 1949: K. voprosu o geostroficheskо vetra. Izv. Akad. SSSR, Ser. Geograf. Geofiz., 13, 281-306.

Tepper, M., 1955: On the generation of pressure-jump lines by the impulsive addition of momentum to simple current systems. J. Meteor., 12, 287-297.

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

VITA

David Scott Ladwig was born 17 April 1952 in Enid, Oklahoma, to Fred T. and Marian A. (Goucher) Ladwig. He attended Oklahoma State University from June 1970 to May 1974 when he was awarded a Bachelor of Science degree in Physical Science. In May 1974, he was commissioned a Second Lieutenant in the United States Air Force. His first duty assignment was to Air Training Command in the basic meteorology program at the University of Oklahoma. After serving tours of duty as a chief forecaster and staff weather officer at Fort Riley, Kansas, and Camp Red Cloud, Republic of Korea, he was assigned to the Air Force Institute of Technology to pursue a Master of Science degree in meteorology at Texas A&M University. The author's permanent mailing address is as follows:

Capt David S. Ladwig
912 South Main
Hennessey, Oklahoma 73742

END

DATE
FILMED
11-81

DTIC