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OBSERVATIONAL AND NUMERICAL STUDIES OF THE LOW-LEVEL
JET STREAM IN THE ATMOSPHERE

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BY

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ABSTRACT

Two cases of low-level jet (LLJ), studied with the Atmospheric Sciences Division MCIDAS facility, support the hypothesis that the LLJ is an integral part of synoptic-scale cyclogenesis. The appearance of an arch with a row of cumulonimbus is discovered at the front of the LLJ. The inertia oscillations in the LLJ are pointed out as part of the quasi-diurnal variation. A plan for further research by numerical modelling is proposed, which will bring more clarification of the mechanics of the LLJ.

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1. Introduction

The low-level jet is the appearance of a wind maximum in the lowest 2 km of the atmosphere. For the purpose of selection of cases, it is practical to use Bonner's (1968) requirement that only a maximum wind of over 12 m s^{-1} is considered, followed with the decrease of wind speed by at least of 2.5 m s^{-1} , all under 2 km elevation above the ground level. The LLJ is recognized as the most important mechanism for transport of water vapor into the storms of middle latitudes (Palmen and Newton, 1969, p.385).

The scientific crew and the technical facilities at the Atmospheric Sciences Division at MSFC/NASA offer unique possibilities to conduct an intensive research of the LLJ. The personnel at this division enjoys high reputation in meteorological research through its publications. The technical facilities at MSFC encompass the McIDAS computerized system for analysis of weather charts and satellite photographs and a battery of computers for modelling of atmospheric processes.

Previous research of the LLJ has led to two different points of view about the dynamics of this jet: (a) theories that the LLJ is a local consequence of momentum transfer in the boundary layer (Blackadar, 1957; Wippermann, 1973), and (b) theories that the LLJ is part of the large-scale dynamical processes in the atmosphere (Uccellini and Johnson, 1979; Djurić, 1981; McNider and Pielke, 1981). Clarification of the controversy between these types of theories is of significant importance, since only with sound theoretical basis we can expect successful modelling and forecasting of the large increase of humidity that occurs before the storms of middle latitudes over North America.

This research opens the way to develop a systematic program for research of the LLJ. The diagnostic part utilizes the most modern analysis tools for proper assesment of physical circumstances that accompany the LLJ. The findings from the diagnostic studies will then be used as initial conditions in the LAMPS model for simulation of the atmosphere. Pairs of computations with altered physics will show the dynamics of the LLJ, when the crucial parameters are altered between the experiments.

2. Objectives

The task of this research is to attempt to identify the mechanism of the LLJ using observations and numerical experimentation. This general objective leads to three sub-tasks:

(a) **Observational:** to use the McIDAS facility for construction of weather charts and satellite photographs that give insight in the mechanism of the

LLJ.

(b) Numerical: to reproduce LLJ under controlled physical circumstances, when the numerical results can be compared to the observed states.

(c) Physical: to follow a definite physical theory, so that the analysis of observations and numerical experimentation can be scientifically guided.

3. Procedures

The exposed objectives were approached when a number of cases with LLJ was analysed using the advanced facilities of McIDAS. After an investigation of days with LLJ and data available on the McIDAS system, it was deemed practical to investigate two cases of LLJ over the Great Plains: of 5-6 May and of 2-3 December, both in 1983. The data needed for this study encompassed the conventional surface and upper-air meteorological observations, and the satellite photographs. This part of research was significantly aided by Mr. Paul Meyer of NASA/MSFC.

The numerical simulation of the LLJ in this project was started using the LAMPS model for simulation of mesoscale atmospheric processes. This model, originally developed by D. Perkey of Drexel University, is operational on the Perkin-Elmer computer at the MSFC. A test run of the model, using the SESAME data (of 24 April 1982) showed that the vertical resolution in the model is adequate for simulation of the LLJ. This part of the research was conducted in close cooperation with Dr. Michael Kalb of USRA/MSFC.

The theoretical basis for the mechanism of the LLJ, as tentatively adopted for this study, is based on my previous work (Djurić, 1981). The geostrophic adjustment, in combination with inertia oscillations, so far seems capable to explain the observed development of the LLJ.

4. The case study of 5-6 May 1983

Radiosonde soundings, as available on the McIDAS, made it possible to extract the maximum wind in the lowest 2 km of the atmosphere, in all stations that showed such a maximum. These results are summarized in Fig. 1 which shows the wind at three subsequent synoptic hours. The first frame shows the first occurrence of the LLJ in this sequence, this was at 0000 GMT over Dodge City, Kansas. In the next observation hour, at 1200 GMT, the LLJ is widespread from West Texas to Nebraska. The intensification of the LLJ can be understood in terms of the boundary-layer theory, which calls for maximum wind speed at the time of day (local dawn) when the stability is strongest. The third observation hour, 0000 GMT 6 May 1983, shows that the

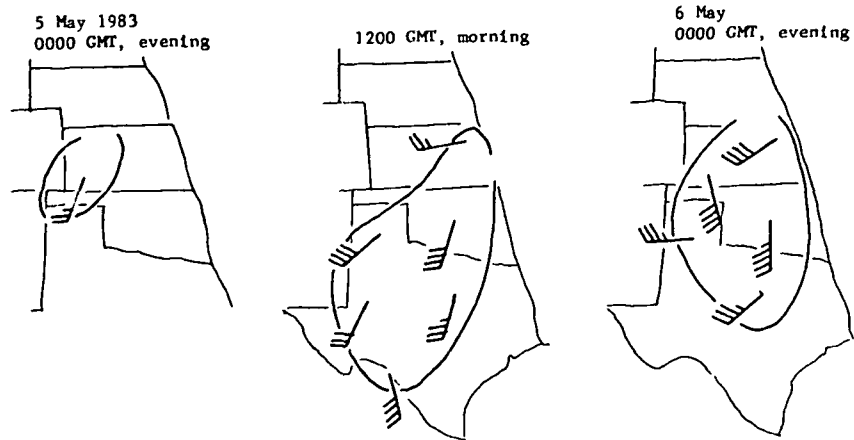


Fig. 1. Development of the LLJ on 5 May 1983. The wind speed is in knots, at the LLJ level. The isotach of 23 kt circles the region with the LLJ. The data outside this region are not plotted.

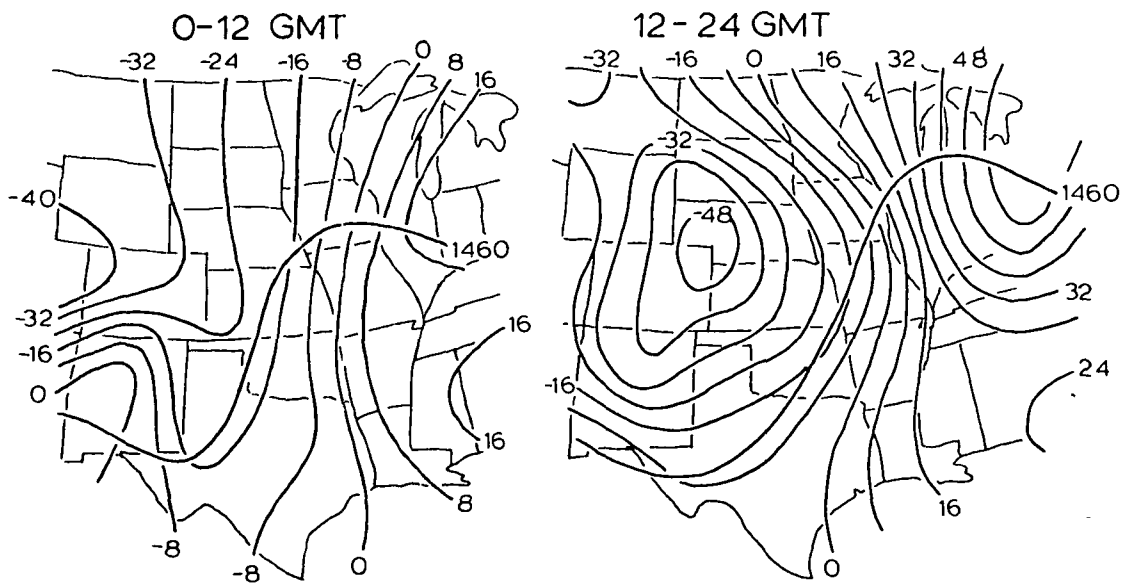


Fig. 2. 12-h height change at 850 mb 0-12 and 12-24 GMT on 5 May 1983, in gpm.

wind speed in the LLJ has further intensified. At this hour the wind reached 44 kt over Oklahoma City. A physical explanation of this wind intensification must be sought in other processes other than the strengthening of the nocturnal inversion. This hour is the local evening. Using the assumption of Uccellini and Johnson (1979), and of Djurić (1981), the general redistribution of pressure in the area can explain the development of the LLJ. The height change at 850 mb between the observation hours every 12 h is shown in Fig. 2. The isallobaric wind of over 1 m s^{-1} can be evaluated over Oklahoma and Kansas. (The expression for the isallobaric wind is shown below in Sec. 7.) Since this wind points across the contours, the air motion is accelerated, thus the LLJ increases with time, irrespectively from the boundary-layer processes.

The other physical problem in this situation is: why does the wind not accelerate in the whole troposphere, instead only in the lowest layer with the LLJ? Now we can recall the premise of Djurić (1981), based on the theory of geostrophic adjustment, that the air can be set in motion only in stable layers. Unstable and neutral layers do not transmit the signal away from the point of disturbance. The existence of the stable layer in the area of the LLJ enables the acceleration of the air. Vertical sections through the atmosphere are shown in Fig. 3 for the period of this study. The location of stations for the sections is shown in Fig. 4.

In the section of 0000 GMT (Fig. 3, top frame) a LLJ can be recognized only at Dodge City, Kansas. The isentropes in this section are quite sparse in the low troposphere, showing low stability, which is understandable for this is the local evening. Next observing hour (1200 GMT, Fig. 3, middle frame) illustrates higher stability, actually an inversion in the surface layer. Now the LLJ is very prominent, maximum speed is over 20 m s^{-1} . The third section, 0000 GMT 6 May 1983 (Fig. 3, bottom frame), is of the evening hour, but now the wind over Oklahoma City (OKC) reached a speed faster than at the previous morning hour.

For the sake of completeness, the environmental condition are documented here with several synoptic charts. At 850 mb (Fig. 4), the isotherms show a warm ridge over the Rocky Mountains and high plains. The warm trough in the contours at 850 mb is quite typical for the circumstances in which the LLJ develops, as it was shown previously by Djurić and Damiani (1980) and Djurić and Ladwig (1983). It is also very interesting to notice that this weather situation is conducive to severe storms. The typical thunderstorm situation, as shown by Doswell (1980), is very similar to the case described here.

The layers from 700 to 200 mb show an almost straight zonal flow over the Great Plains. Out of these, only the 200-mb chart is shown here. The contours on this chart show this zonal flow (Fig. 5). The subtropical jet stream is located zonally over Texas. The region of Oklahoma-Kansas,

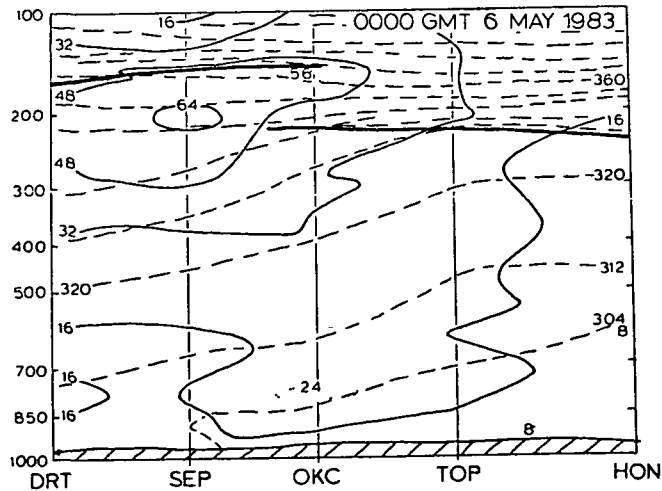
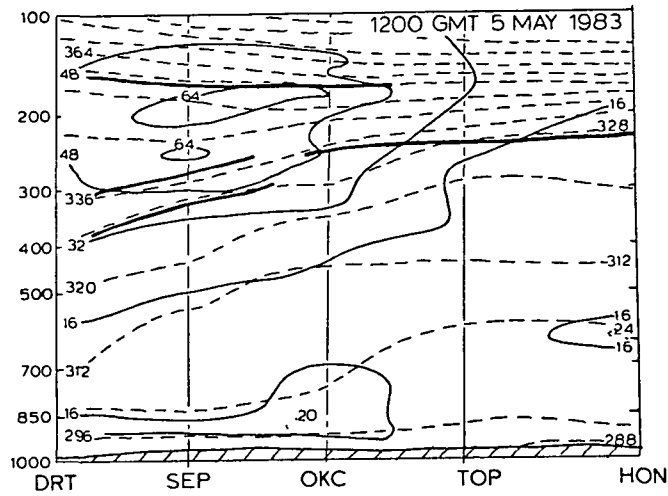
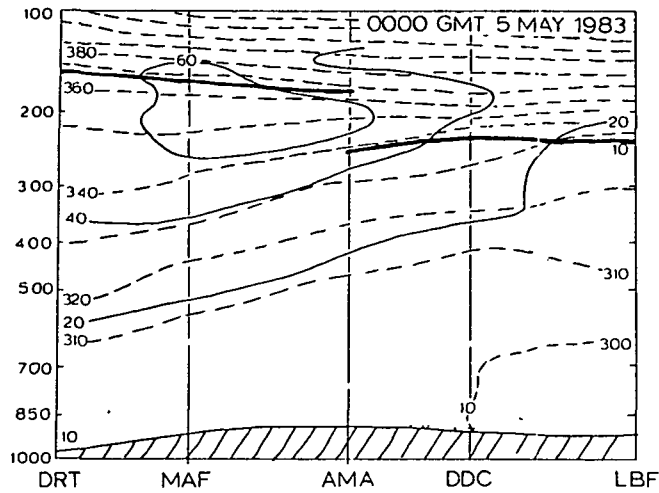


Fig.3. Vertical sections through the atmosphere at 0000 (top) 1200 (middle) and 2400 GMT (bottom) on 5 May 1983. Full lines are isotachs in m s⁻¹, with intermediate values dotted. Dashed lines are isentropes in K of potential temperature. Heavy lines indicate the tropopause and the subtropical front.

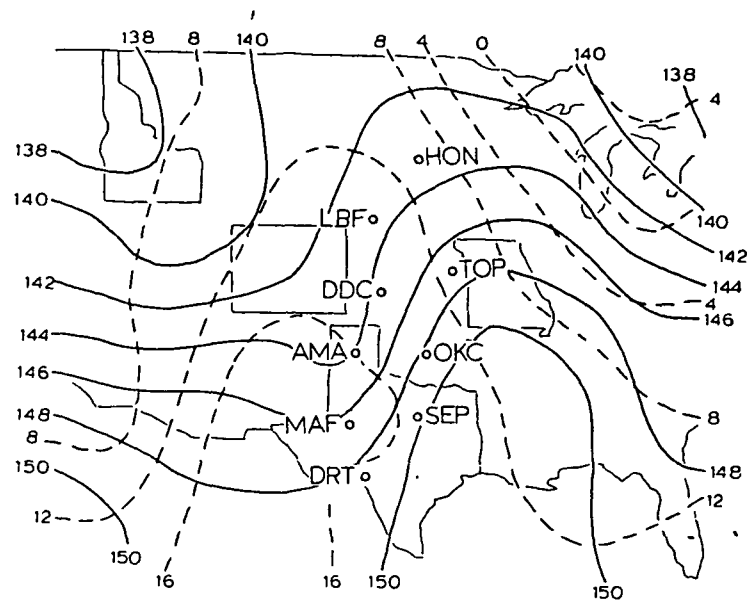


Fig. 4. 850-mb contours (full lines, 10 gpm) and isotherms (dashed, °C) at 1200 GMT 5 May 1983. The stations used in Fig. 3 are shown by the 3-letter call names.

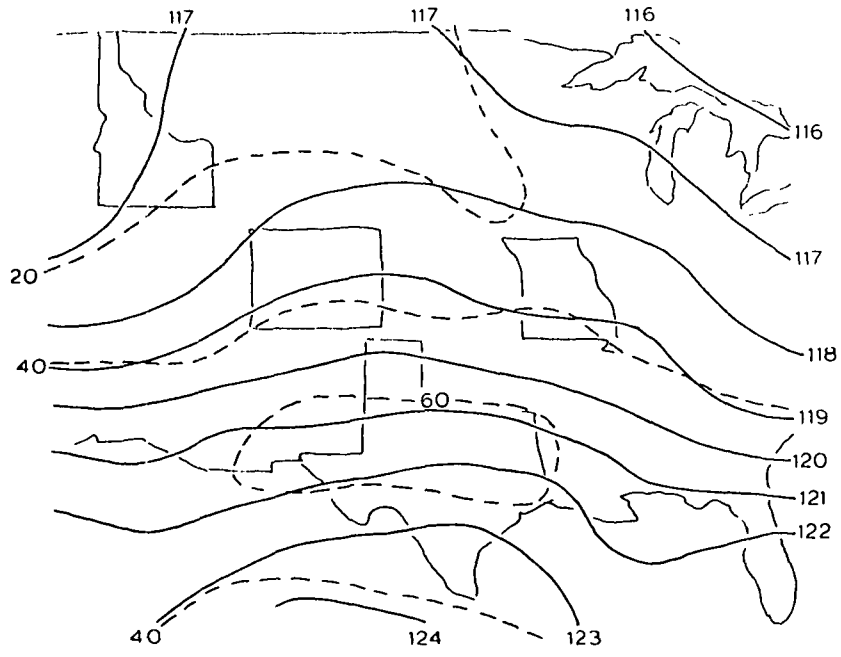


Fig. 5. 200-mb contours (full, intervals of 100 gpm) and isotachs (dashed, 20 m s⁻¹) 12 GMT 5 May 1983.

where the LLJ develops is not associated with large curvature of the flow or with an exit from a jet streak. The polar jet stream is located near Great Lakes. There is a trough in the polar jet stream over the West Coast, this trough is related to pressure fall over the western third of United States. This pressure fall has been illustrated in Fig. 2. It may be pointed out that the trough in the lee of the Rocky Mountains is not in the immediate vicinity of the polar jet stream or the polar front.

In conclusion, the data from this case may be interpreted to support, but in any case not to contradict, the premise that the LLJ develops in a strong isallobaric field in a stable layer near the earth's surface.

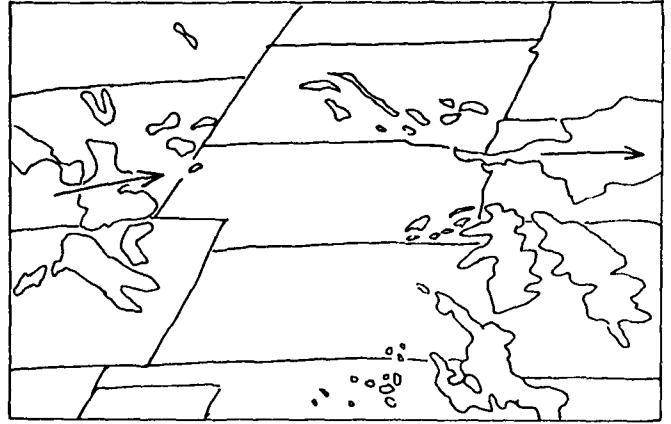
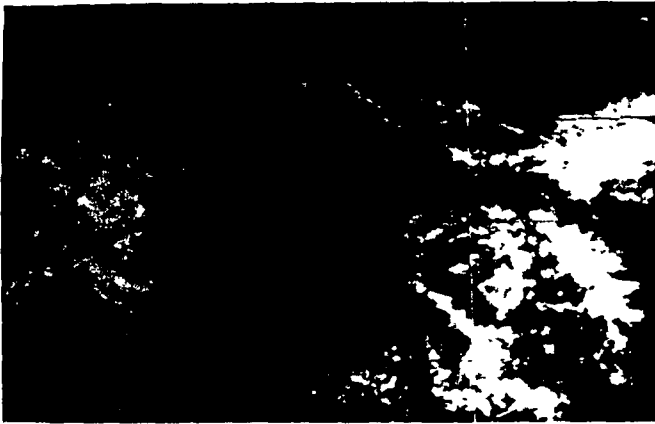
5. The "outflow boundary" with the LLJ

The satellite photographs of 5 May 1983 show an interesting case of formation of several cumulonimbus in a ring on the mesoscale that looks similar to the thunderstorm outflow boundary, but in this case there were no thunderstorms in the area to serve as a source for this outflow. In the multitude of clouds on this day, no still photograph reveals clearly a semicircle of cumulonimbus as the looping of hourly photographs does. The phenomenon in question is illustrated in Fig. 6, where three selected photographs are shown, at intervals of 3 h. These photographs are taken in visible light, however, most of analysis was done in hourly infrared photographs that are not shown here. For the purpose of reporting, the photos in the visible spectrum show a better contrast.

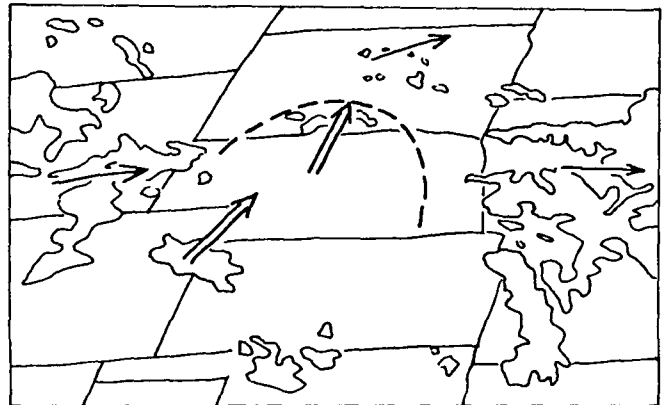
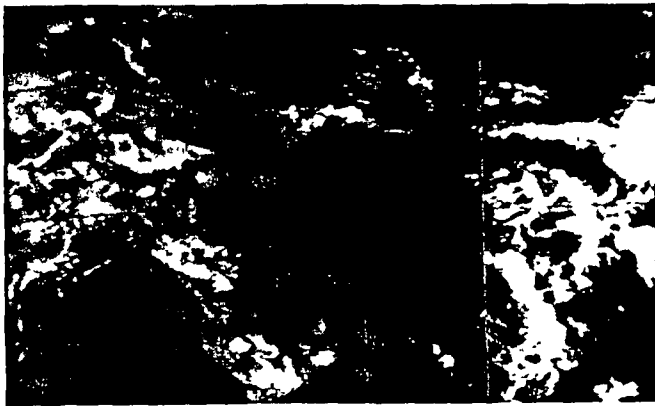
All clouds in the first frame (1500 GMT) move with the wind in the middle and higher troposphere, that is zonally, as shown by arrows in the sketches that accompany the photos. The region covered by the LLJ (as seen in Fig. 1) covers a cloud-free area over Kansas and Nebraska. By 1800 GMT, second frame in Fig. 6, the northern extent of the LLJ can be identified in the cloud photograph by a number of clouds that move toward the north. These clouds are quite noticeable when the loops of hourly photographs are examined. In sketches in Fig. 6 the northward-moving clouds are shown within a dashed arc. In the sketches, the motion of the air within the LLJ is shown by double arrows. The circularly arranged clouds along the arc are strikingly similar to the arches of new convection cells that occur in the outflow from thunderstorms (e.g. Maddox *et al.*, 1981). In the last frame of 2100 GMT, the arc with convective clouds penetrated deeper to South Dakota and to Iowa. The western end of the arc in Colorado already assumed the general zonal flow, so that this part of the arc started retreating into the area occupied by the southerly LLJ.

The progression of the arc with clouds can be interpreted as an appearance of a shallow warm front where all lifting results in convection since the atmosphere is conditionally unstable. The clouds are in the middle-latitude air in a raised trade wind inversion with which the LLJ is

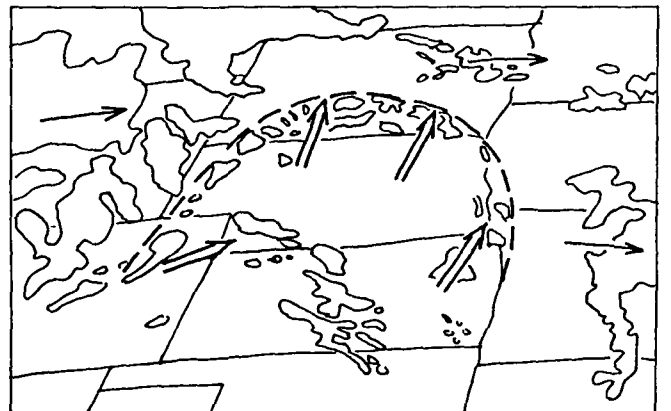
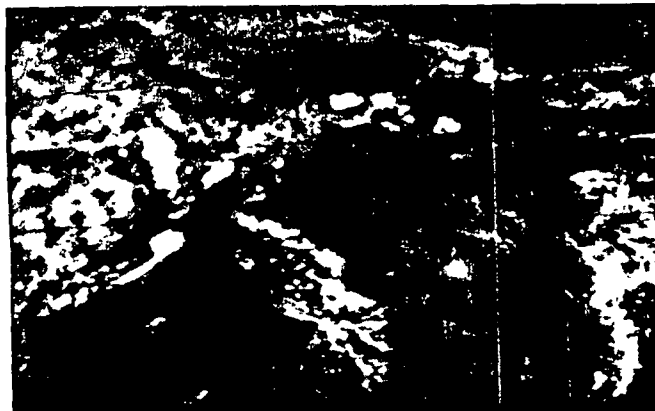
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15 GMT



18 GMT



21 GMT

Fig.6. Satellite photographs of the Great Plains in visible light, at intervals of 3 h, on 5 May 1983, and sketches with interpretation of the photographs side-by-side.

associated.

6. The case of 2-3 December 1983

The development of the LLJ on 2 December is shown in Fig. 7. This figure contains the LLJ observations and the positions of the polar front at 850 mb and the upper tropospheric jet streams. It may be seen again that the LLJ develops in the warm sector, between two loops of the polar front. This warm sector was prominent at 850 and 700 mb, but was almost absent in the temperature field at the surface. The LLJ in Fig. 7 is shown at 0000 GMT, which is the local evening hour. This makes it difficult to interpret this jet as an inertia wave that started with decoupling of stable layers at night in the boundary layer. However, it is unfortunate that the soundings of the morning hour of 1200 GMT were not available on the McIDAS system during my short stay at MSFC.

There were several lows and highs in the area, but the LLJ occurred nearest to the low that developed in northeast Texas on the 3 December. There was a prominent pressure fall over Texas and Louisiana, as shown in Fig. 8. In the same figure the location of the center of the low of 3 December is shown at two times: at 0600 and 1800 GMT. The LLJ retreated during the 2 December until it was confined to the area south and east of the place where the low in Texas developed on 3 December. The development of the LLJ was again related to the isallobaric field (Fig. 8), but the northern part of the chart was under an isallobaric field in which the gradient of height tendency ($-\nabla(\partial z/\partial t)$, with minus) pointed south. In that part the LLJ and any southerly flow did not develop. The LLJ appeared only in the southern part of the region where the gradient $-\nabla(\partial z/\partial t)$ pointed north.

The isotherms at the earth's surface, which are not commonly drawn in routine weather analysis, are shown in Fig. 9 for 0000 GMT 2 December 1983. The distribution of temperature shows a remarkably zonal form, with the only larger exception of a cold trough in the lee of the Rocky mountains from West Texas to western Nebraska. A hardly noticeable thermal ridge can be detected over northeastern Texas and Oklahoma. This ridge moved to the Mississippi river between Missouri and Illinois in 24 h, with a small increase in amplitude.

The development of the LLJ during 2 December 1983 confirms the synoptic-scale character of this jet. Also, its development further southeast than the usual position in West Oklahoma gives indication that the sloping terrain of the high plains is not a necessary element. It is, however, possible that the effects of sloping terrain contribute to the dynamics of the LLJ (McNider and Pielke, 1981). The climatological frequency of the LLJ over high plains can be interpreted as a consequence of the sloping terrain (Bonner, 1968). On the other hand, the frequency of cyclogenesis in that area ("Colorado cyclone") is a more likely direct cause

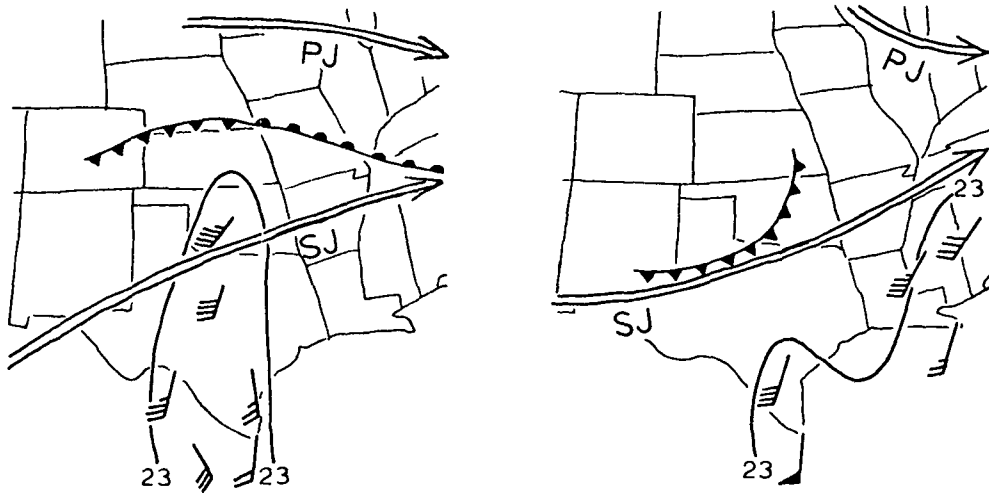


Fig. 7. LLJ on 2 December 1983. Wind speed in knots at the LLJ level. The isotach of 23 kt circles the LLJ, other data are not plotted. The front at 850 mb is shown by the sawtooth line. The polar jet (PJ) and the subtropical jet (SJ) are shown by the double arrows.

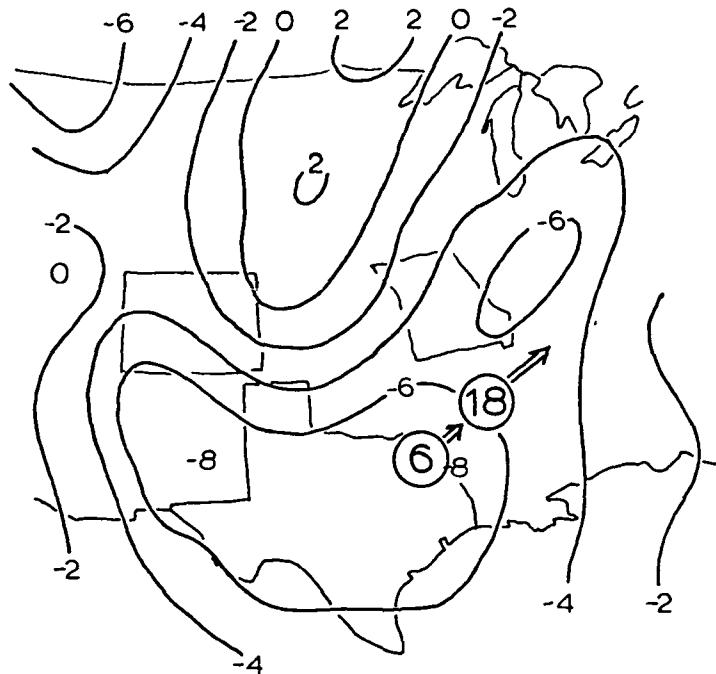


Fig. 8. 24-h height change between 0000 and 2400 GMT on 2 December 1983 at 850 mb, in gpm. The positions of a surface low in Texas and Arkansas at 0600 and 1800 GMT on 3 December are shown by circled numbers.

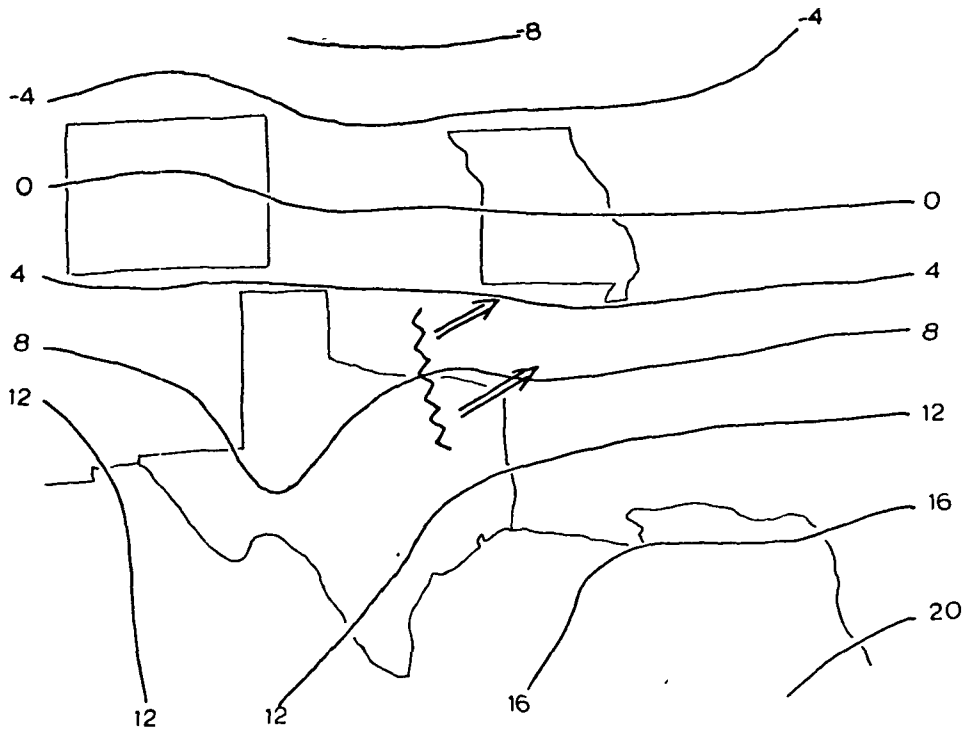


Fig. 9. Isotherms at the earth's surface, 1200 GMT 5 May 1983.

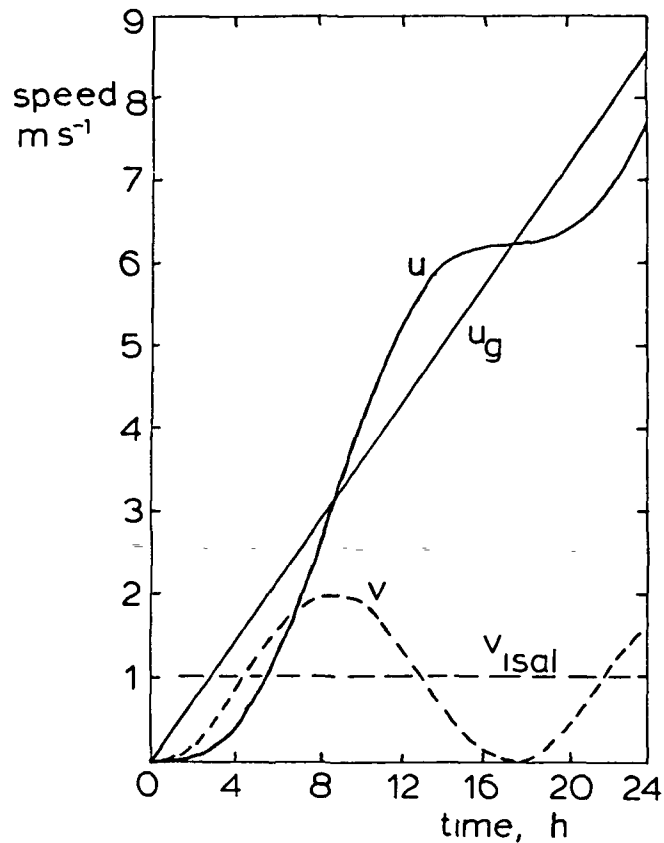


Fig. 10. Theoretical variation of wind and isallobaric wind. The wind components are u , v . The isallobaric wind is v_{isal} , and u_g is the geostrophic wind.

of frequent LLJ.

7. The LLJ as an inertia oscillation

Several theories of LLJ show that a sudden change of forces may cause the LLJ. These theories assume that the LLJ is formed by nocturnal decoupling of layers (Blackadar, 1957), by heating of the sloping boundary layer (McNider and Pielke, 1981) or by onset of cyclogenesis (Djurić, 1981). The LLJ under these circumstances should show inertia oscillations. In order to clarify this possibility, here an example is computed that demonstrates some of the basic properties of acceleration of the air in a stable layer.

If we consider a layer of air where the horizontal variation is comparatively small and the influence of friction is negligible, the air movement may be approximated by the following equations of motion:

$$\begin{aligned}\frac{du}{dt} &= f v \\ \frac{dv}{dt} &= f v_g - fu\end{aligned}\quad (1)$$

Here u and v are the x and y components of wind, v_g is the component of geostrophic wind under consideration. The other component of the geostrophic wind is set equal to zero by the turning of the coordinate system. The Coriolis parameter f is considered constant for this discussion. Therefore, the case of a steadily increasing pressure field is considered, defined by

$$\frac{du_g}{dt} = \text{const.} = 10^{-4} \text{ m s}^{-2}$$

The general solution of (1) is

$$\begin{aligned}u &= u_0 \cos ft + v_0 \sin ft + u_{g0} + t \frac{du_g}{dt} \\ v &= -u_0 \sin ft + v_0 \cos ft + \frac{1}{f} \frac{du_g}{dt}\end{aligned}$$

where u_0 and v_0 are the arbitrary constants of integration.

We are interested in the simple particular solution that shows the initial state of rest, when a pressure tendency suddenly appears. Then the particular solution is

$$\begin{aligned}u &= u_{g0} + \frac{du_g}{dt} \left(t - \frac{1}{f} \sin ft \right) \\ v &= -\frac{du_g}{dt} (1 - \cos ft)\end{aligned}$$

The trigonometric terms show the inertia oscillations, while the other terms

represent the part analogous to the normal mode:

$$u_n = u_{g0} + t \frac{du_g}{dt} = u_g$$
$$v_n = - \frac{du_g}{dt} = v_{isal.} = \text{const.}$$

This shows that the isallobaric part of wind $v_{isal.}$ is constant and it suddenly appears at the time of onset of the pressure tendency.

This theoretical situation is represented in Fig. 10. The slanted straight line is the increasing geostrophic wind and the dashed straight line is the isallobaric wind. The motion of air oscillates around the "normal", nonoscillating part ($u_g, v_{isal.}$).

The implications of this theoretical example are that similar oscillations occur in nature, albeit more complicated. We cannot know whether the observation comes from the peak or valley in the oscillations. However, it can be seen that the ageostrophic component of flow is never too large. It is possible that the ageostrophic component in the atmosphere appears larger if the value of du_g/dt is larger.

The flow in this situation is accelerating, even if it is not much different from the geostrophic balance. This may explain the origination of the LLJ in the synoptic-scale isallobaric field. A decline of the LLJ is not illustrated here. It is assumed that an opposite isallobaric gradient or friction in absence of pressure force will influence the LLJ to weaken and eventually disappear.

8. Modeling studies

The LAMPS (Limited Area Mesoscale Prediction System) model is one of the most advanced mesoscale models in the world. It has been demonstrated that it can successfully simulate a number of weather processes (e.g. Kalb and Perkey, 1985). Recently, this model was made operational at the Atmospheric Sciences Division of NASA/MSFC, using the Perkin-Elmer computer. The usefulness of this model for simulation of the LLJ can be demonstrated by the wind profile taken from an experiment which was not specially tailored for the study of the LLJ (Fig. 11). This wind profile is from a grid point close to Oklahoma City where the LLJ developed. For comparison, two observed wind profiles with LLJ are shown in the same figure. Those two are not from the same weather situation, but from the similar situation in the case of 5 May 1983, described above. Similarity of the wind profile in the lower layers is apparent. This shows that the LAMPS model is suitable for simulation of the LLJ. There are differences between

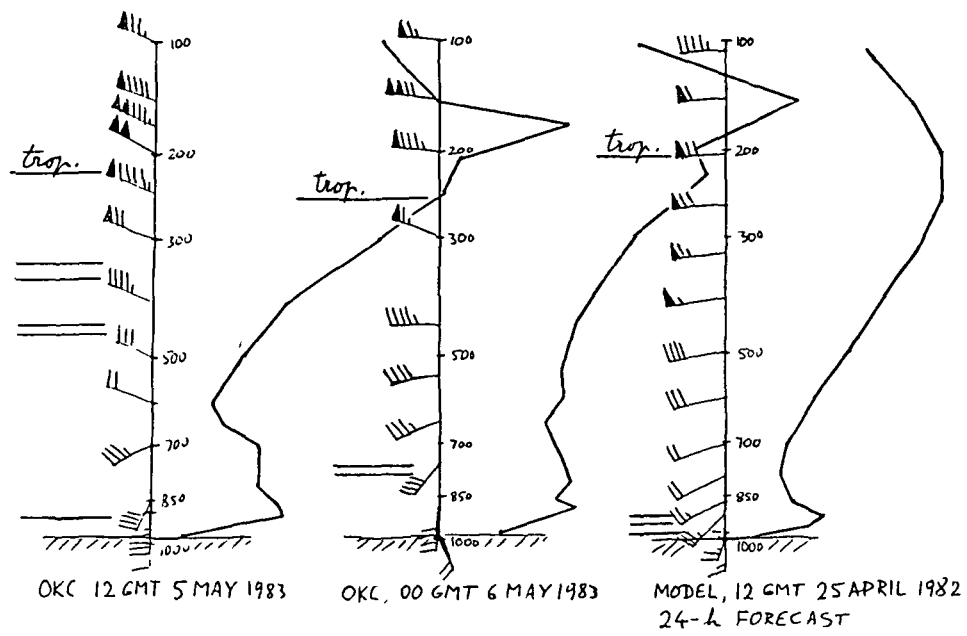


Fig. 11. Wind profiles from the LAMPS model and observed at OKC 0000 GMT 5 May 1983.

the observed and simulated wind profiles in upper layers, these can be attributed to the difference in the structure of the atmosphere: the case of 5 May 1983 had the subtropical jet in the upper troposphere, and the LAMPS case was under the polar jet.

After discussing several possibilities for further work on the problem of LLJ development with Dr. M. Kalb of MSFC, we decided to run several parallel experiments with the model in which a schematic weather situation will be used as the initial condition. In this way it will become clear which factors influence the development of the LLJ, since all the "irregularities" of observations will not be present. We designed a model initial state that contains the baroclinic zone of the polar front, with waves such that the cyclogenetic region is situated in the middle of the computational domain. This scheme is illustrated in Figs. 12 and 13. In Fig. 12 there is a plane view of the computational domain. Between the two sinusoids labeled FN and FS is the frontal zone, 600 km wide. The amplitude of the frontal zone is 1200 km. The meridional vertical section through the frontal zone is shown in Fig. 13, with several isotherms and discontinuity surfaces at the front and tropopause. Cyclogenesis is expected in the model in the region of positive vorticity advection in the middle of the computational domain. One other experiment will be computed with addition of an inversion south of the polar front, simulating the existence of the trade wind inversion which is typical for the warm sector of the cyclones. This inversion is typical for the generation and development of the LLJ. Experiments of this type will clearly single out the crucial factors in the development of the LLJ.

9. Conclusions

The research done during my short stay at MSFC yielded several results that show the possibilities for the study of the LLJ, as are

(a) The diagnostic studies can be done efficiently using the McIDAS facility for handling weather data. There are still some difficulties in such work, e.g. unavailability of some data, but as the time progresses, such difficulties will be less present.

(b) Numerical modeling can be done at MSFC with great efficiency, mainly due to the available model and adequate computer facility.

As the examples in previous sections show, further work on the LLJ can and will be continued, since this task is well defined, useful for future application and suitable for the facilities at MSFC.

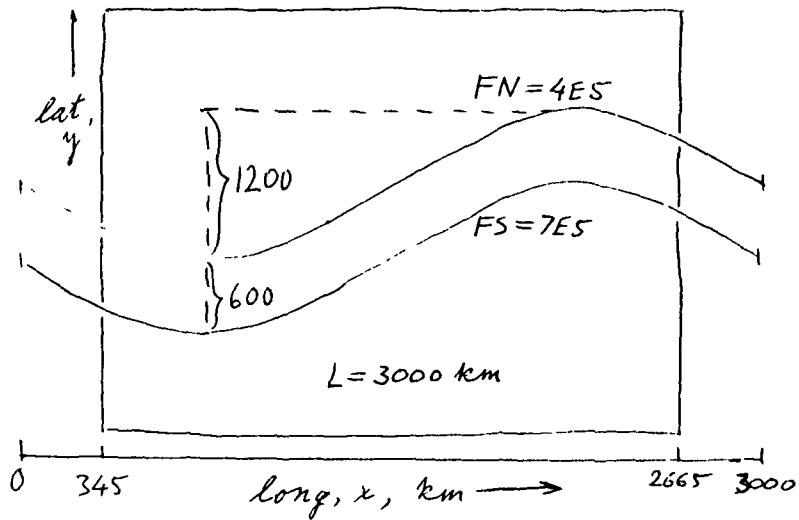


Fig. 12. Proposed initial conditions for the experiment with LLJ, plane view. The frontal zone is between the two sinusoids.

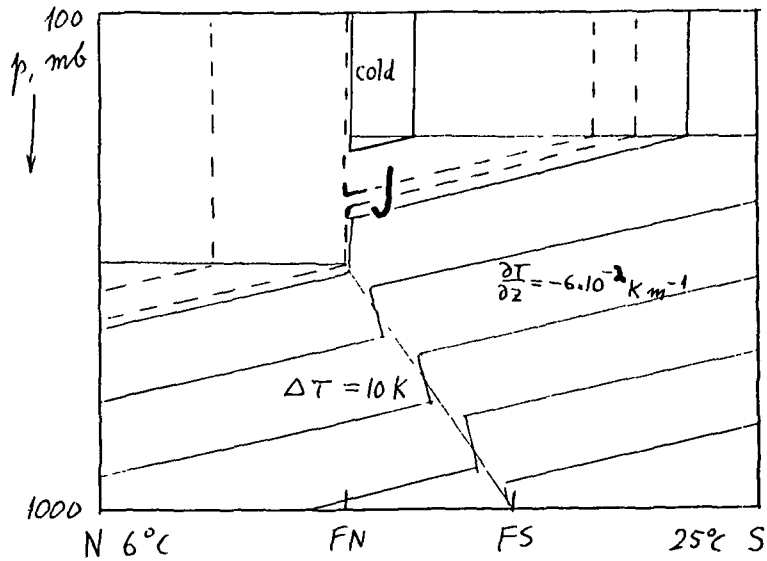


Fig. 13. Proposed initial conditions for the experiment with LLJ, vertical section. Isotherms, front and tropopause are shown.

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