The Great Plains Low-Level Jet (LLJ) During the Atmospheric Radiation Measurement (ARM) Intensive Observation Period (IOP)-4 and Simulations of Land Use Pattern Effect on the LLJ

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Introduction

The Great Plains low-level jet (LLJ) is an important element of the low-level atmospheric circulation. It transports water vapor from the Gulf of Mexico, which in turn affects the development of weather over the Great Plains of the central United States. The LLJ is generally recognized as a complex response of the atmospheric boundary layer to the diurnal cycle of thermal forcing. Early studies have attributed the Great Plains LLJ to the diurnal oscillations of frictional effect (Blackadar 1957), buoyancy over sloping terrain (Holton 1966), and the blocking effects of the Rocky Mountains (Wexler 1961). Recent investigations show that the speed of the LLJ is also affected by the soil type and soil moisture (Fast and McCorcle 1989). Some studies also suggest that synoptic patterns may play an important role in the development of the LLJ (Uccellini 1980; Chen and Kpaeyeh 1992).

Land surface heterogeneities significantly affect mesoscale circulations by generating strong contrasts in surface thermal fluxes (Mahfouf et al. 1987; Segal et al. 1989). Thus one would expect that the land use pattern should have effects on the LLJ's development and structure. In this study, we try to determine the relative roles of the synoptic forcing, planetary boundary layers (PBL) processes, and the land use pattern in the formation of the LLJ using the observations from the Atmospheric Radiation Measurement (ARM) Intensive Operation Period (IOP)-4 and numerical sensitivity tests.

Analysis of the Observations

During ARM IOP-4 (June 15-25, 1993), LLJs were well observed on June 16, 17, 21, 22, 23, and 24 (Figure 1). During the period, powerful storms swept through the nation's midsection, accompanied by tornadoes, high wind, large hail, and heavy rain. According to the National Oceanic and Atmospheric Administration (NOAA) weekly weather summary for the two weeks of June 13-19 and June 20-26, 1993, the LLJs played an important role in the weather events.

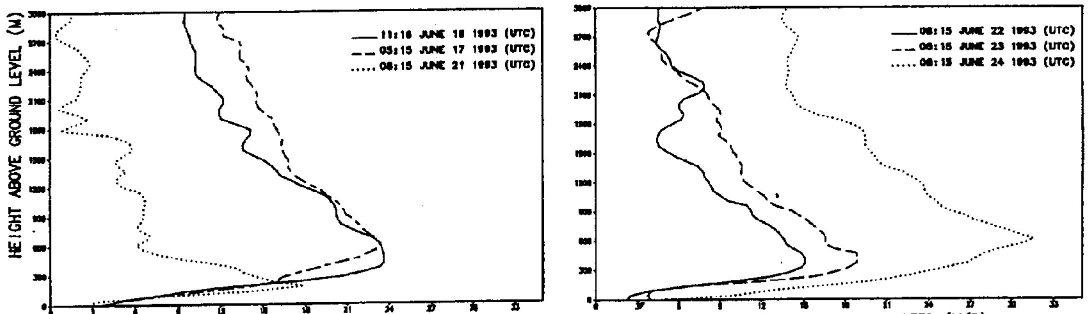


Figure 1. The low-level jets during ARM IOP-4, June 15-25 1993 (soundings at Kingman Station, Kansas).

The analysis of 300-mb maps at 0000 UTC for the six LLJs shows that two basic synoptic circulation patterns existed. The synoptic patterns for the LLJs on June 16, 17, 23, and 24 consisted of a strong trough over the Rockies and a ridge located in the eastern part of the country. The synoptic patterns for LLJs on June 21 and 22 consisted of a strong ridge over the Great Plains and a trough over the eastern United States. These two synoptic patterns are shown in the 300-mb maps at 0000 UTC for two typical days (June 21 and 24) (Figure 2). For June 21 and 22, the LLJs were at a relatively lower position with a weaker speed. The jet on June 22 had the lowest speed (15.1 ms^{-1}), while the jet on June 24 had the strongest speed (31.5 ms^{-1}). One jet (June 23) reached its peak at 0500 UTC, three jets (June 21, 22, and 24) reached their peaks at 0800 UTC, and the other two at 1100 UTC. Thus, there are some similarities in the evolutions of the six LLJs: each LLJ was associated with nocturnal temperature inversion and had strong diurnal oscillation, formed in the late afternoon or early evening, reached its peak in the next day early morning, and lasted for about 9-12 hours. Each LLJ was found in the ambient southerly flow over the central and southern Great Plains. The sounding profiles for the six LLJs indicate that they were mainly established by boundary layer processes and their position and strength were significantly affected by synoptic patterns.

Simulations of Land Use Pattern Effect on the LLJ

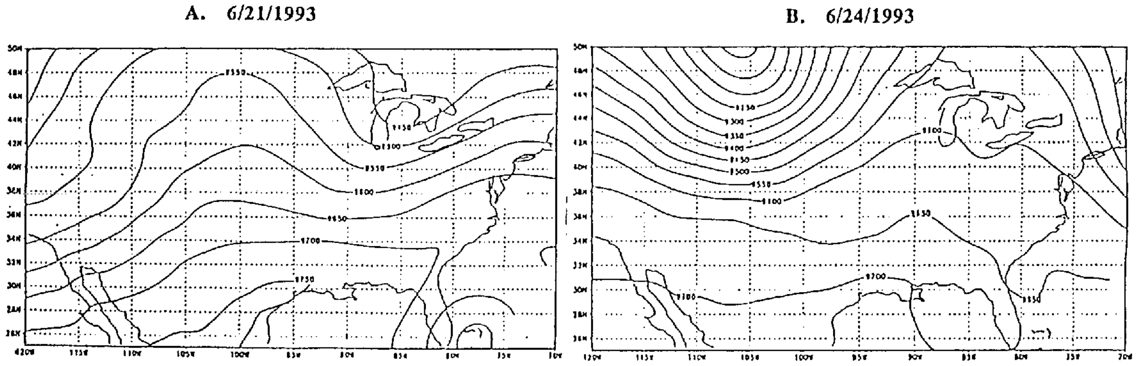
Model Description

This study uses the North Carolina State University mesoscale model which consists of three systems: the atmosphere, the vegetation, and the soil. The atmospheric portion of the model is three dimensional, anelastic, and hydrostatic with a terrain-following sigma (σ) coordinate system. The surface layer is based on the similarity relations of Businger et al. (1971). Above the surface layer, prognostic turbulent kinetic energy and turbulent dissipation equations are used. A two-time-level fourth-order Crowley scheme is used for horizontal advection, while a quadratic upstream interpolation scheme is used for vertical advection.

The model is linked with the soil-vegetation system to investigate the effects of the surface forcings on the LLJs. The parameterization of the soil-vegetation system is similar to that of Deardorff (1978). A single layer of vegetation with negligible heat capacity is assumed to be present and is characterized by its physical height, canopy density (shielding factor), optical properties (albedo and emissivity), and stomatal resistance. The foliage surface temperature is determined by the energy budget for the foliage layer. The air temperature and moisture within the canopy are represented by corresponding properties of the air immediately above the canopy, the soil, and the vegetation itself. The soil system consists of a shallow top layer and a deep bottom layer. The force restore method is used to calculate the soil surface temperature (Tg) which depends on the energy budget at the surface and a restoring term containing the deep soil temperature. The soil surface moisture is estimated in the same way.

Numerical Experiments

The model was run in its two-dimensional version in this study. The model domain is 450 km long and 10 km high with 45 grids in the horizontal and 25 in the vertical. The vertical grid spacing varies from 30 m to 1000 m with higher resolution at lower levels. The time step is



A. 6/21/1993

B. 6/24/1993

Figure 2. The 300 mb maps for 00 UTC 21 and 24 June 1993.

10 seconds.Two ideal land use patterns dependent on vegetation type, soil type, soil moisture, and their distribution were chosen for this study. One is of oasis type which is an area of vegetation within arid surroundings. The other is with contrasting bare soil and vegetated areas. The soil and vegetation input parameters are given in Table 1. Two simulations were run for each pattern with and without initial wind. The initial surface temperature is 297 K with a potential temperature lapse rate of $+3.5\ \mathrm{K\ km^{-1}}$ below 3000 m and $+3.0\ \mathrm{K\ km^{-1}}$ above 3000 m. The specific humidity corresponds to sounding at 1100 UTC June 21, 1993. The initial wind is southerly and uniform with a magnitude of $10\ \mathrm{ms^{-1}}$. All the simulations commenced at 0800 local solar time (LST) which corresponds to time when the sensible heat fluxes become effective in the development of the convective PBL. The latitude used in the model is 37.4°N which is the latitude of Kingman station, Kansas. In order to show the diurnal variations of the LLJ structure, the model was run for 48 hours for each simulation.

Results

The results from the 24-48 hour simulation were analyzed. For the oasis simulations, the oasis consisting of dense forests with a height of 10 m and a shielding factor of 0.99 is located at the center of the model domain with a width of 110 km. For the simulation without initial wind, the simulated fields of temperature and wind are very similar to the results by Segal et al. (1988). Horizontal gradient of sensible heat flux is evident as a large temperature difference exists between the oasis and its surroundings. There are two symmetric circulation cells. At 0200 LST, the magnitude of the V component is about five times that of the U component. Two pair of low and high centers of V component developed below 3000 m. Normally, if there is a synoptic southerly (northerly) wind, the high centers (the low centers) would develop into two LLJs. The results from the simulation with initial wind at 0200 LST are given in Figure 3. Two LLJs are clearly displayed in the field of the V component, one located at a height of 450 m and the other at 1800 m. The vertical motion in this case is about two times stronger than the motion in the previous case. The evolution of the LLJ with lower position is shown in Figure 3 by the vertical profile of the horizontal wind speed at grid point 10 at different times. Both the jets formed around 2200 LST and reached their peak $(17.5\ \mathrm{ms^{-1}})$ around 0200 LST.

Table 1. Soil and Vegetation Input Parameters

1. Soil	**Sand**		
Cv	$1.256 * 10^6\ \mathrm{J\ m^{-2}\ K^{-1}}$	k	$0.293\ \mathrm{J\ m^{-1} K^{-1} s^{-1}}$
Dh	$0.233 * 10^6\ \mathrm{m^2 s^{-1}}$	z_o	0.01 m
T	23.8°C		
2. Vegetation	**Forest**		
Z_a	10.0 m	σf	0.99
R_{smin}	$100.0\ \mathrm{s^{-1}}$	αf	0.15
E_f	0.98	z_o	1.0 m

Cv = soil volumetric heat capacity; k = soil thermal conductivity; D_h = soil thermal diffusivity; z_o = roughness; T = soil temperature; Z_a = vegetation height; σf = vegetation shielding factor; R_{smin} = minimum stomatal resistance; α_f = albedo of the vegetation; E_f = emissivity of the vegetation.

For the contrasting bare soil and vegetated area, the contrast consists of a relatively dry bare soil region of 210 km width in the west and a wet soil region of 240 km width in the east covered by dense forest. For the simulation without initial wind, a large difference in potential temperature exists between the dry bare soil region and the dense forest with wet soil. The circulation generated in this case is stronger than in the oasis case. Two regions of maximum winds are clearly displayed in the V wind field at 0020 LST. The simulation fields of V and W components of the wind and potential temperature at 0200 LST for the simulation with initial wind are provided in Figure 4. A narrow jet structure is at the 600-m level in the V field. The evolution of the LLJ is shown in Figure 4. The LLJ formed around 2200 LST and reached its peak $(21\ \mathrm{ms^{-1}})$ around 0200 LST.

The simulated LLJs are generated by a strong horizontal temperature gradient caused by land surface heterogeneities and a southerly synoptic wind. Although the LLJs are under ideal conditions, they have some similarities to the observed ones: 1) They have significant diurnal oscillation, forming at midnight and reaching their peak in the early morning; 2) they are generated in the ambient southerly flow; and 3) the heights of the LLJs near the surface are consistent with the observations.

Summary

Analysis of the soundings during ARM IOP-4 indicated that the synoptic circulation patterns for the LLJs can be classified into two categories. The LLJs under the more favorable synoptic pattern have relatively higher position and stronger speed. However, each of the six LLJs is associated with a temperature inversion and has significant diurnal oscillation. The simulated LLJs also have significant diurnal oscillation, form around 2200 LST, and

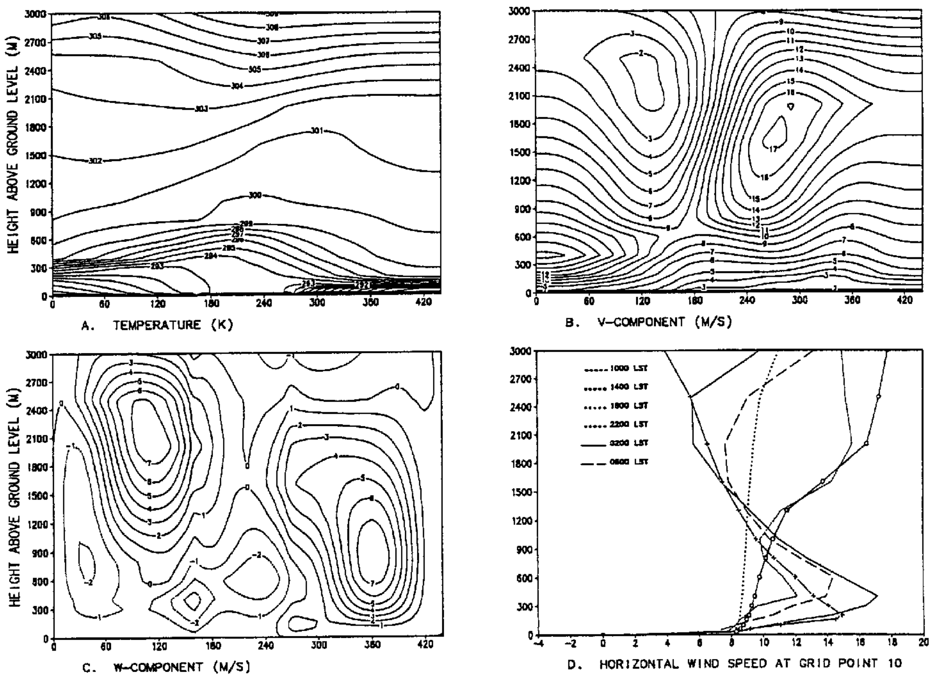


Figure 3. Simulation results from the Oasis Case.

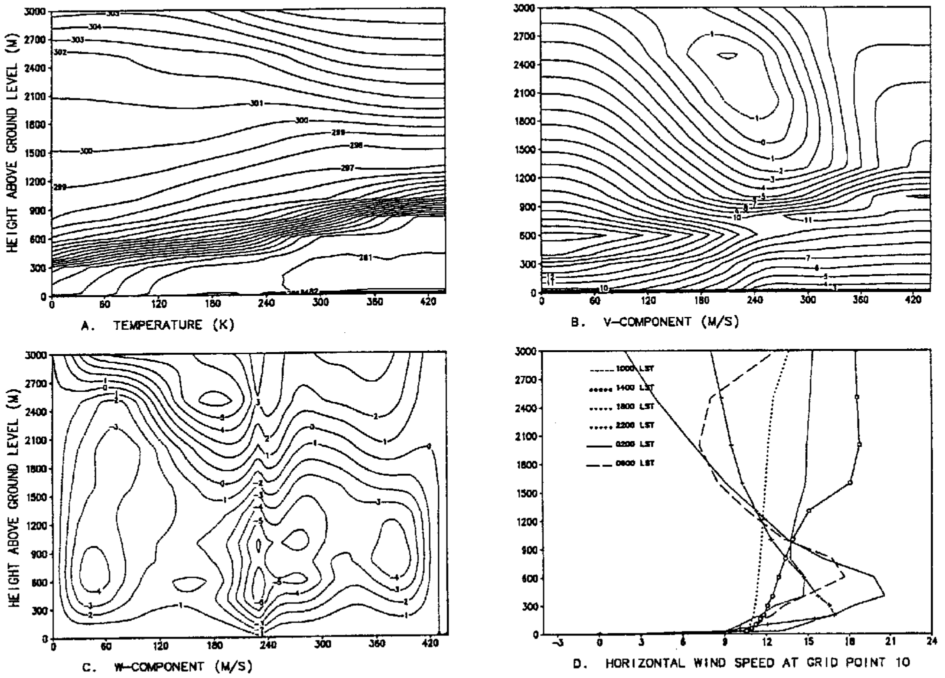


Figure 4. Simulation results from the bare soil-forest contrast.

reach their peaks around 0200 LST. Both the soundings and the numerical tests indicated that each of the LLJs is mainly established by the boundary layer processes. The mesoscale circulations generated by the surface heterogeneities strengthen the LLJs.

Acknowledgments

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