2.4.3. Low-level (especially nocturnal) Jet

The broadest definition of a low-level jet (LLJ) is simply any lower-tropospheric maximum in the vertical profile of the horizontal winds.

A LLJ can occur under favorable synoptic conditions anywhere in the world.

Of practical interest is their impact on the transport of moisture. Of theoretical interest is the large amount of vertical wind shear associated with them and the observation that they are typically supergeostrophic by a large (>50%) amount.

A large number of specific geographic locations all over the world have been identified as especially favorable for LLJ development. Among these locations is the Great Plains region of the United States, in which one of the most significant LLJs, in terms of its impact on precipitation and severe weather, occurs. The Great Plains LLJ has consequently been studied more than any other.

<u>Definition</u>

- Fast moving current of air near the surface.
- Large wind shear ($\frac{\partial \vec{V}}{\partial z}$) above and below the jet level.
- Maximum wind speed at least 12-16 m/s (peak speeds up to 30 m/s observed)
- Wind speed above jet 50-75% or less of the maximum.
- Strong lateral shear on both sides. Width typically about 200-300 km.

Examples of LLJ:

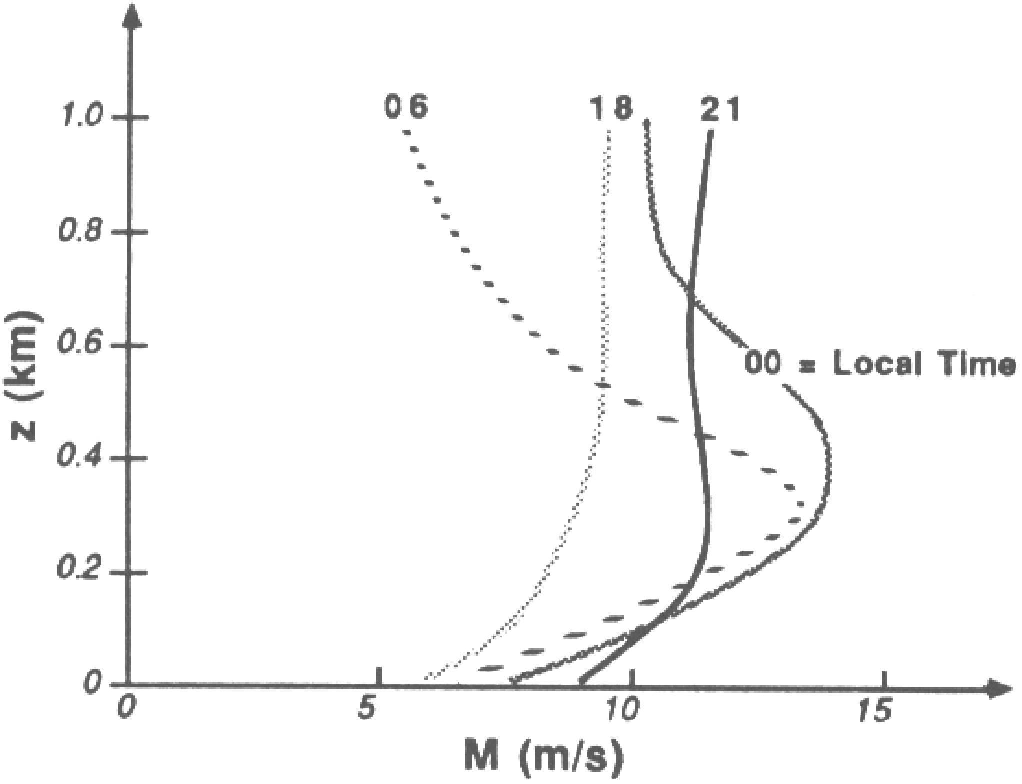
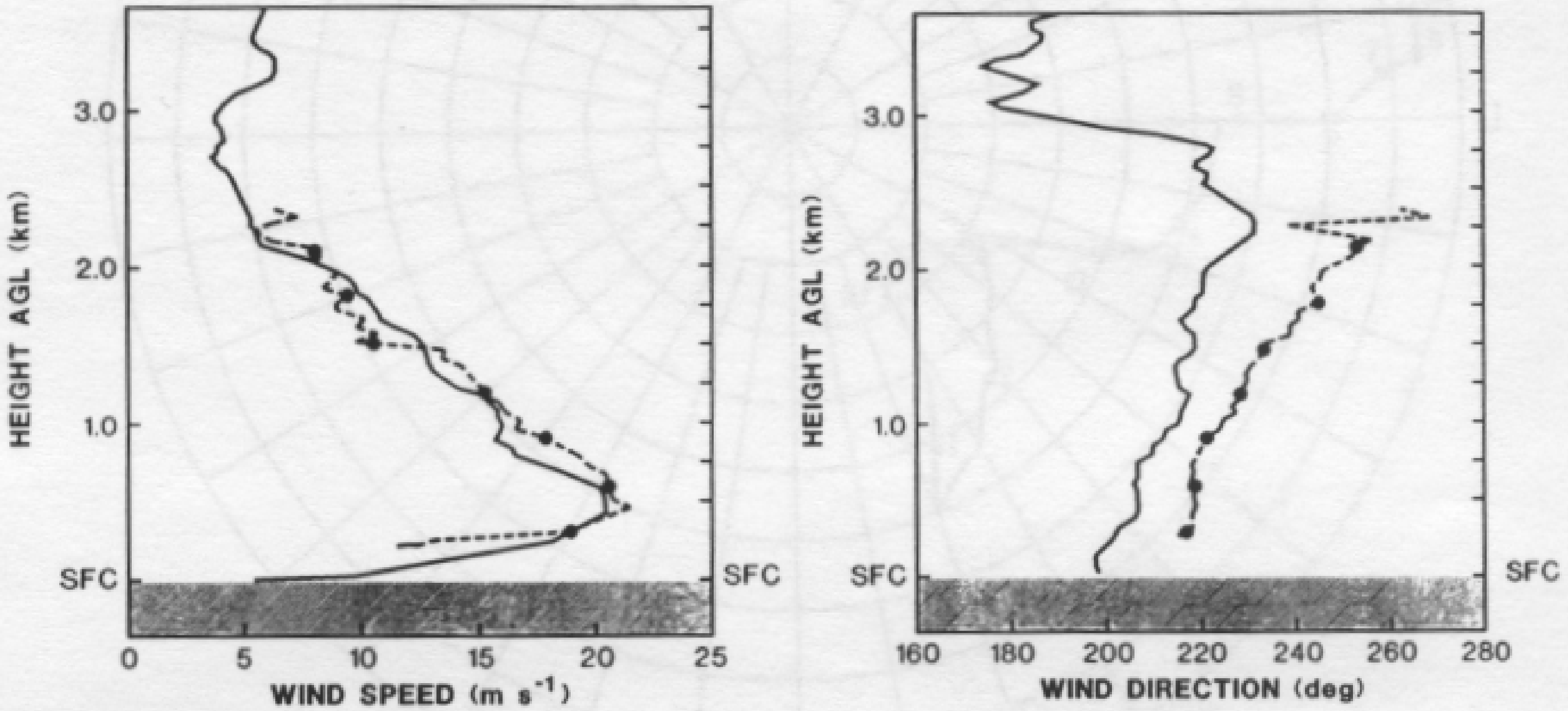


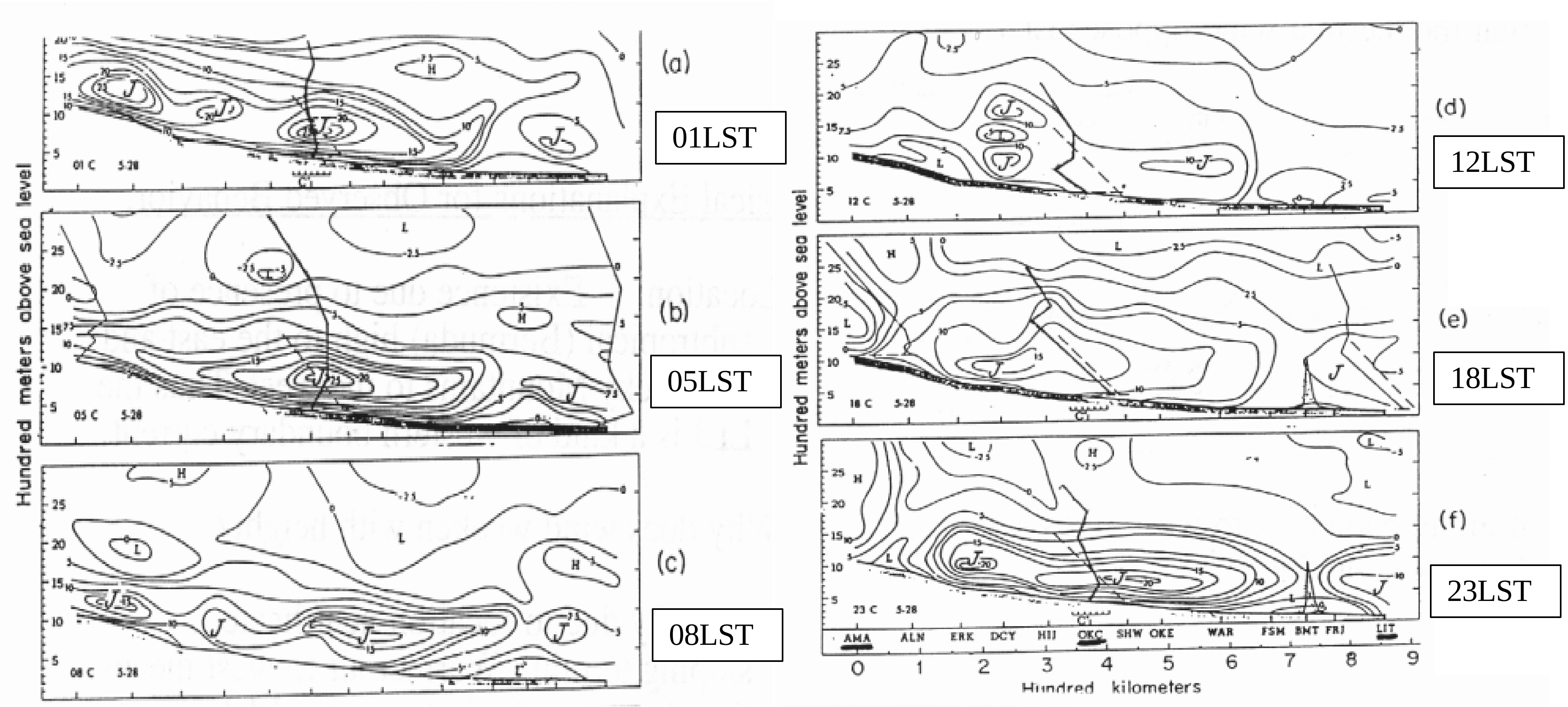
Fig. 12.15 Nocturnal jet evolution during night 13-14 of Wangara. (After Malcher and Kraus, 1983.)



(a) (b)

Figure 2.93 Example of a southerly low-level jet in the Southern Plains of the United States (at Norman, Oklahoma) 0930 UTC (0430 CDT), July 29, 1988. (a) Wind speed as a function of height (km AGL) from CLASS rawinsonde data (solid line) and Doppler radar VAD (velocity-azimuth display) data (dashed line); (b) wind direction (degrees) as a function of height (km AGL) as in (a). Note the pronounced maximum in wind speed from the south-southwest at about 400 m AGL (from Stensrud et al., 1990; courtesy R. Maddox, NSSL and the American Meteorological Society).

Nocturnal enhancement of LLJ:



Climatology of LLJ

In the U.S., most common as a southerly jet over the Great Plains, especially in the spring and summer.

Also found, for example, in Australia (Koorin Jet and Southerly Buster) and East Africa (Somali Jet).

For the U.S. Plains version:

- Strong diurnal oscillation with strongest wind speeds at night.
- Average height 500-1000 m AGL. Near the level of nocturnal inversion.
- Often the maximum winds are supergeostrophic.

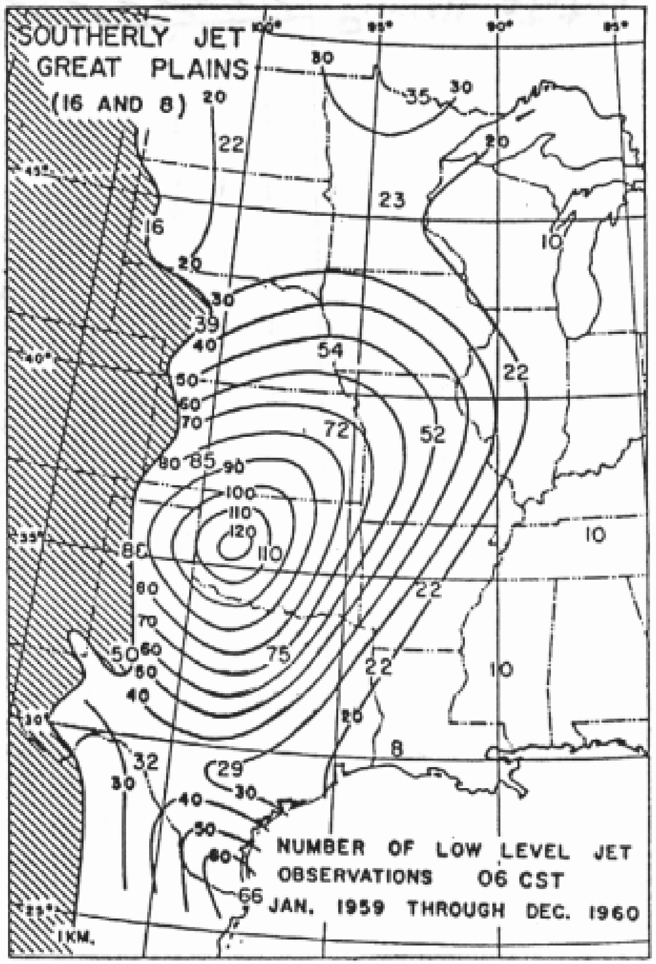
In the climatology study of (Bonner 1968), it was found that

- LLJ tended to have a wind maximum near 800 meters above ground level; that strong jets were primarily a nighttime feature;

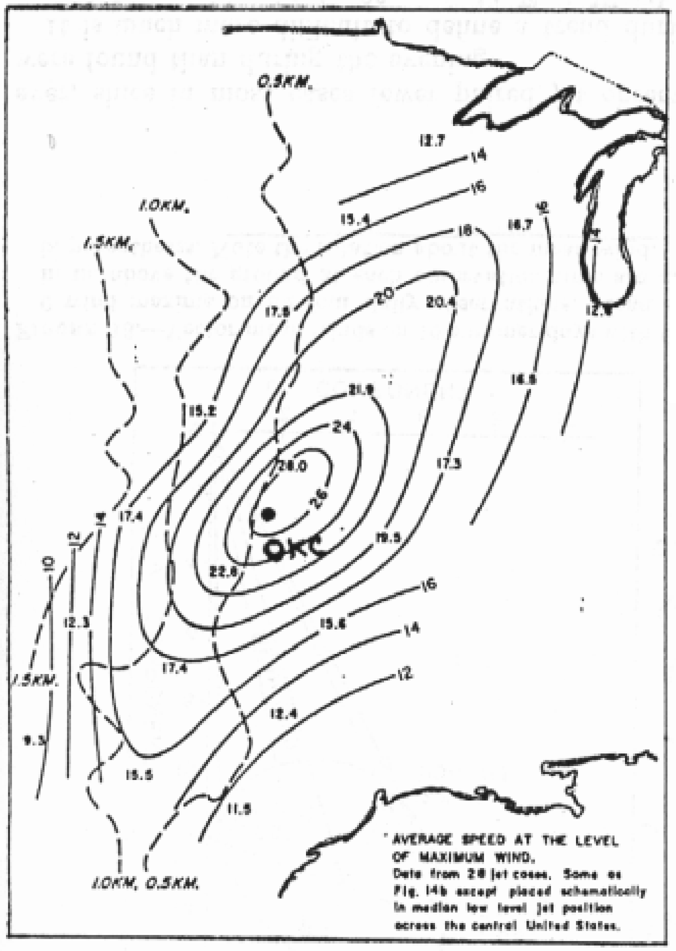
- LLJ occurred with greatest frequency during the spring and summer;

- The states of greatest activity include: Texas, Oklahoma, Kansas, Nebraska, Iowa, Missouri, and Arkansas;

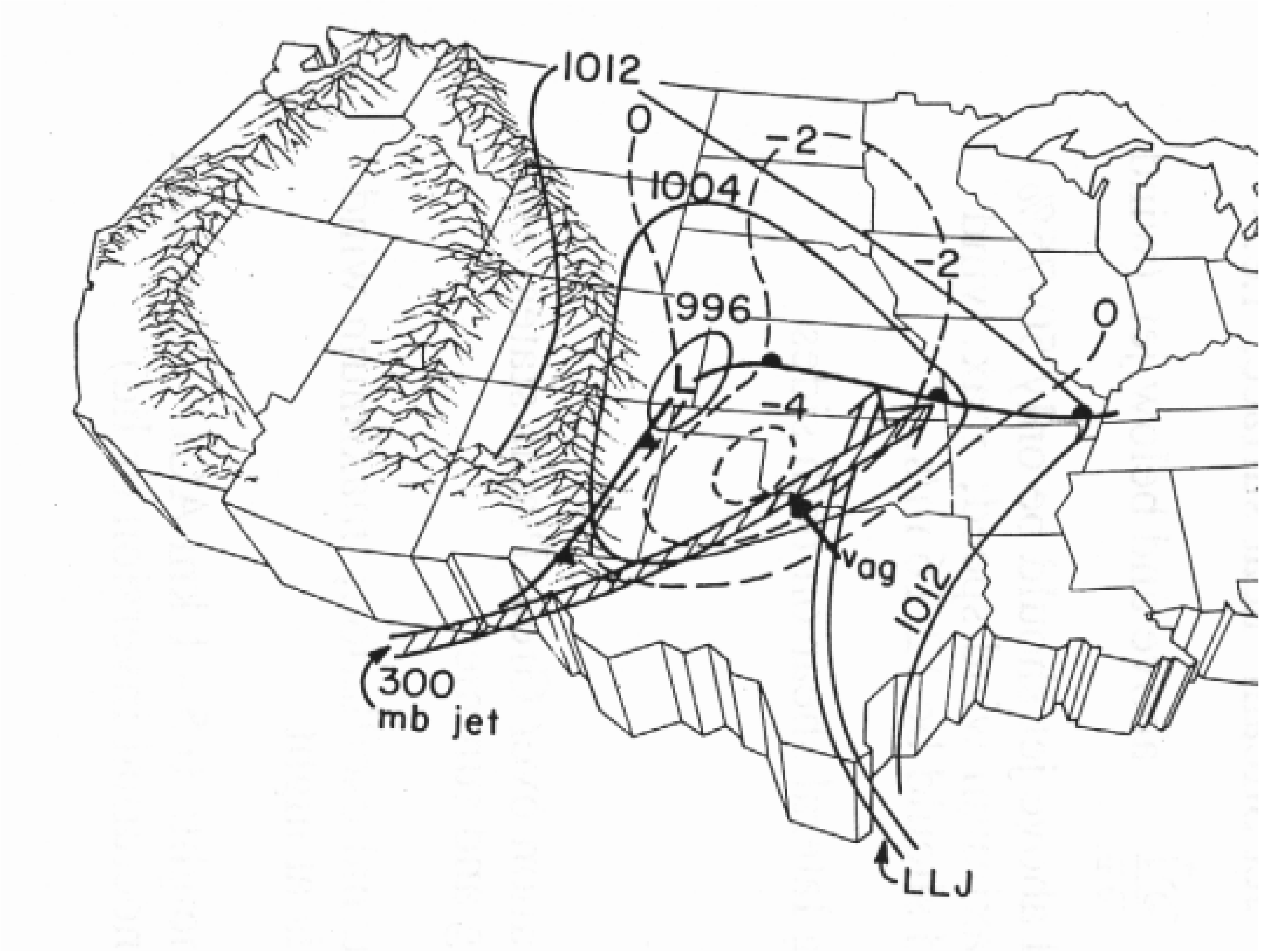
- Favorable synoptic conditions for LLJ formation are those which have a strong west to east pressure gradient across the Great Plains and an uninterrupted flow of air from the Gulf of Mexico.



RE 11.—Numbers of Criterion 2 "southerly jet" observations at 06 CST. Two years of data.



RE 15.—Mean isotach pattern (m. sec.$^{-1}$) at the level of maximum wind.



A more recent study by Whiteman et al. (1997) has shown that

- 50% of LLJ **maxima** actually occur **below 500m**
- the **temporal wind maximum** typically occurs **around 2am LST** (local standard time).

Meteorological Importance

- Increased **northward transport of moisture** at jet level.
- Increased low-level **convergence at nose of jet**.
- Involved in **sustaining convection at night** – partly responsible for nighttime thunderstorm maximum in Plains.

The low altitude and southerly flow of the LLJ make it **a key element in the return-flow cycle of air from the Gulf** of Mexico (a typically springtime event). In this cycle, northerly flow advects dry, typically cool continental air out over the Gulf of Mexico where it is modified by surface processes and gains moisture. To complete the return-flow cycle, this modified air then advects northward back onto the continent by way of low-level winds. The **LLJ is a principal mechanism by which this moist and unstable air from the Gulf is advected northward into the United States where it ultimately becomes precipitation**.

Higgins et al. (1997) found that **low-level flow of moisture from the Gulf of Mexico at night is increased by 48% from mean values** when a LLJ is present.

Arritt et al. (1997) showed that the widespread **Great Plains flooding event of 1993 was associated with a prolonged period of strong LLJs**.

LLJ can also promote convection by inducing uplifting from **convergence along the nose of the jet** (Zhong *et al.* 1996) which **can combine with divergence aloft from an upper-level jet** (Beebe and Bates 1955).

The strong nocturnal phase of the jet is widely believed to be particularly important in promoting nighttime convection.

The **LLJ** has been linked to the occurrence and intensity of mesoscale convective systems and **appears to be an essential ingredient in the environment that produces mesoscale convective complexes**. This is due presumably to the enhancement of both warm advection and the advection of moist, unstable air (Maddox 1983).

Further, the presence of a **LLJ, especially when combined with an upper-level jet, provides a veering of winds with height that is favorable for the development of severe weather and tornadoes** (Uccellini and Johnson 1979).

Causes of Nocturnal LLJ:

- Inertial oscillation.
- Baroclinicity over sloping terrain.
- Coupling with return circulation in the jet streak.
- Others

We will consider first two causes only here, as they relate to boundary layer dynamics:

Inertial Oscillation (first cause)

One of the perhaps most important theories for LLJ was due to Blackadar (1957).

This theory **accounts for** both the **daily oscillation** in jet intensity **and** for the significantly **supergeostrophic velocities** observed during the nocturnal phase.

Blackadar explains that:

- The cycle of the LLJ as an inertial oscillation that relies on the **retardation to subgeostrophic speeds** of lower tropospheric air **due to vertical, turbulent mixing** with the heated surface during the day.

- Once surface heating ceases near **nightfall**, the layer of air in contact with the ground undergoes radiative cooling, becomes statically stable, and **decouples from the layer of air above** which becomes nearly frictionless and turbulence free and accelerates due to the synoptic pressure gradient.

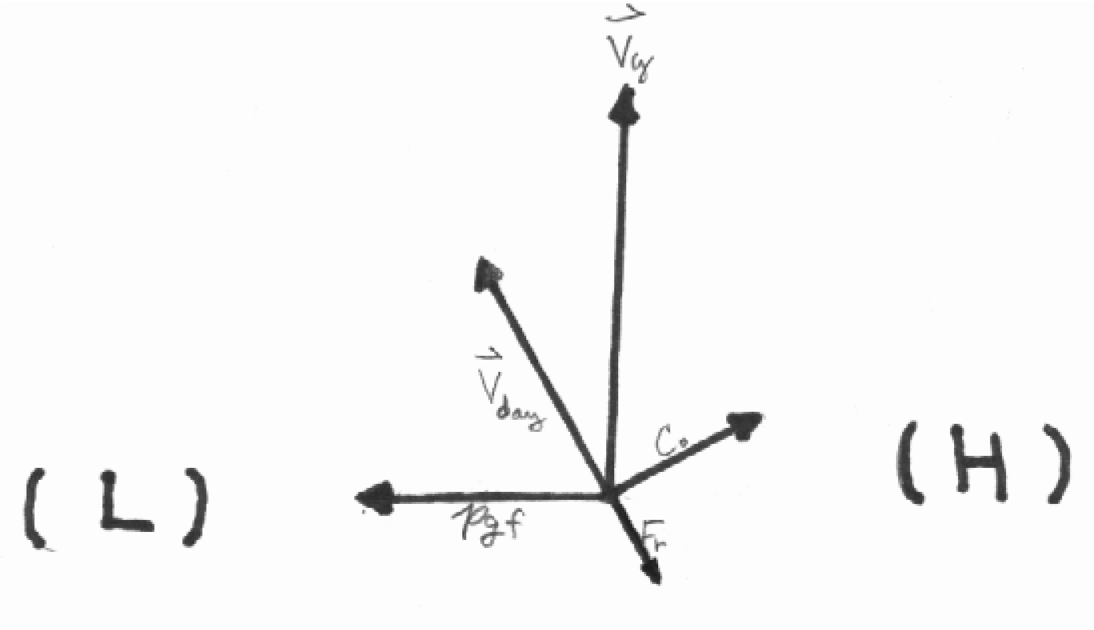
- The effect of the **Coriolis force** on this accelerating, frictionless air stream is to **cause an inertial oscillation with supergeostrophic speeds** being reached after several hours.

Consider the classic example of an oscillating system, a pendulum. The stable (or balanced) position of a pendulum is pointing straight down. A push of the pendulum to one side will cause it to return to the balance point, but its momentum will carry it past that point, and it will swing up on the other side.

Now consider the “Balance Point” for atmospheric motion: Geostrophy.

Frictional drag keeps the wind below geostrophy in the mixed PBL during the day.

At night, the stable layer reduces drag to only the lowest tens of meters.
Air above that accelerates as friction is “released”.



Mathematically, consider the behavior of the ageostrophic flow, after friction is released:

$$\frac{\partial}{\partial t}\left(u-u_g\right)=f\left(v-v_g\right) \qquad \text{(a)}$$

$$\frac{\partial}{\partial t}\left(v-v_g\right)=-f\left(u-u_g\right) \qquad \text{(b)}$$

Solve this system of equations. Differentiate (a) with respect to time:

$$\frac{\partial^2}{\partial t^2}\left(u-u_g\right)=f\frac{\partial}{\partial t}\left(v-v_g\right)$$

Substitute from (b)

$$\frac{\partial^2}{\partial t^2}\left(u-u_g\right)=-f^2\left(u-u_g\right)$$

Similarly

$$\frac{\partial^2}{\partial t^2}\left(v-v_g\right)=-f^2\left(v-v_g\right)$$

These have solutions of the form:

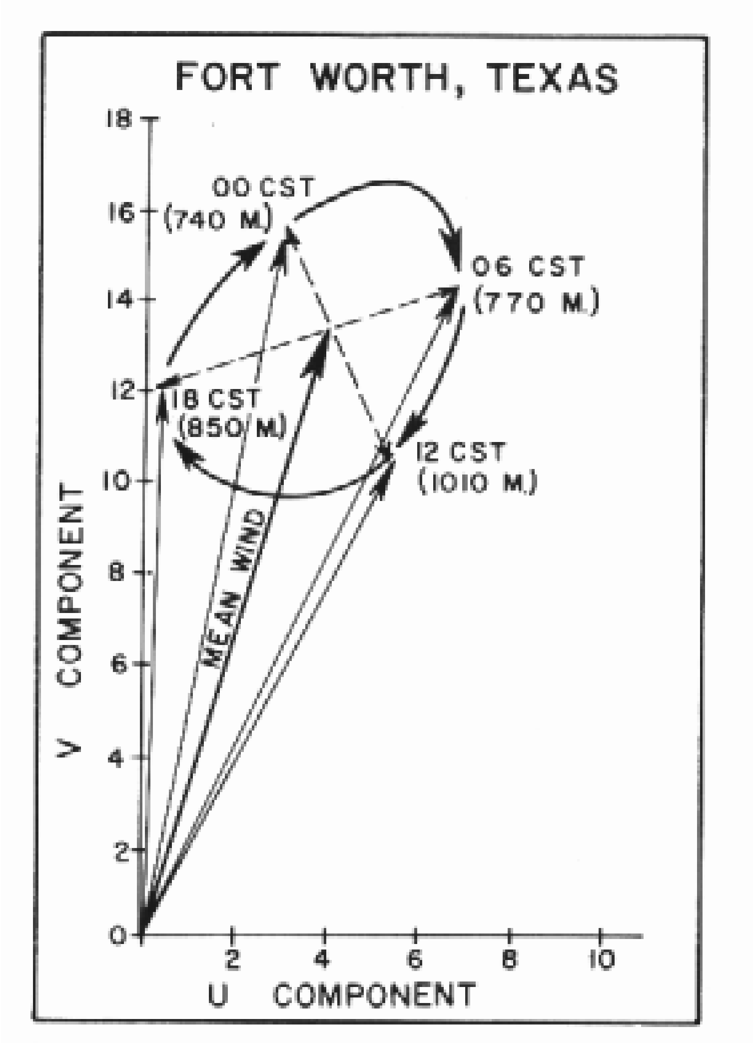
$$\left(u-u_g\right)=A\sin(ft+a)$$
$$\left(v-v_g\right)=A\cos(ft+a)$$

Period $T=2\pi/f$

Period as a function of Latitude

Latitude	*Period*
20	34.9 hr
25	28.3 hr
30	23.9 hr
35	20.9 hr
40	18.6 hr
45	16.9 hr
50	15.6 hr

A Real Data Case



Baroclinicity Over Sloping Terrain (second possible cause):

Theories other than the Blackadar theory have been proposed to account in whole or part for the LLJ. One mechanism analyzed by Holton (1967) describes the nature of the LLJ as a response to the diurnal heating and cooling of sloping terrain, which results in a periodic variation in thermal wind and a consequent surface geostrophic wind oscillation.

This mechanism makes no appeal to variations in turbulent mixing and has the advantage of explaining why the LLJ tends to be located over the (gently sloped) Great Plains, which the Blackadar theory does not address.

Thermal wind relations:

$$\frac{\partial u_g}{\partial z} = -\frac{g}{f\overline{\overline{T}}}\frac{\partial \overline{T}}{\partial y}$$

$$\frac{\partial v_g}{\partial z} = \frac{g}{f\overline{\overline{T}}}\frac{\partial \overline{T}}{\partial x}$$

where $\overline{T}$ is a layer-mean temperature.

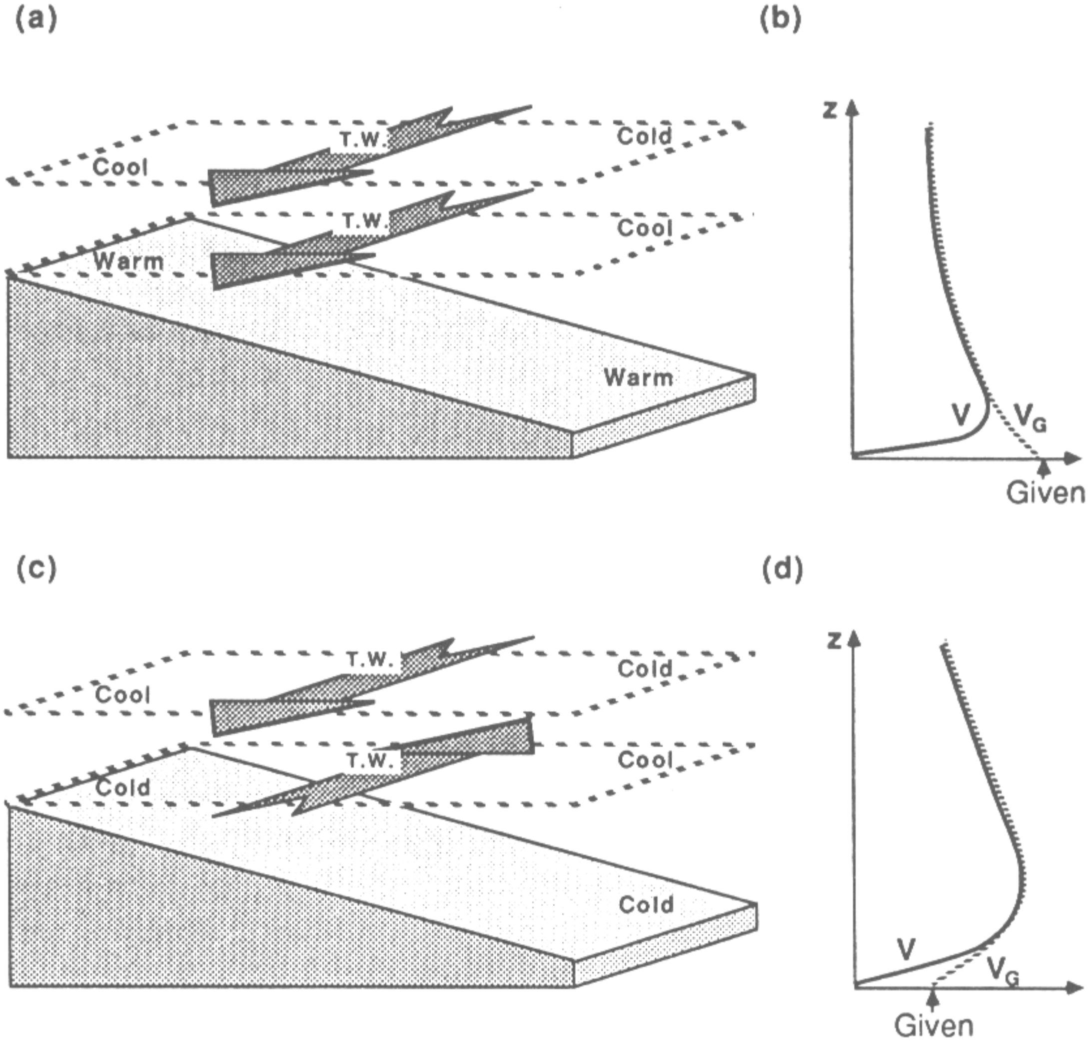


Fig. 12.17 Diurnal oscillation of the low level jet due to thermal wind (T.W.) forcings over sloping terrain.

Daytime (a, b):

Solar insolation warms ground and forms mixed layer with near-adiabatic lapse rate so that west-to-east temperature gradient – measured along a horizontal surface – is negative $\frac{\partial T}{\partial x} < 0$ near the ground and aloft. So thermal wind: $\frac{\partial v_g}{\partial z} < 0$. Mixing is strong during the daytime and tends to blur the effect so that you don't get a jet.

Nighttime (c, d)

Ground cools more quickly than the air and the gradient is reversed, west-to-east temperature gradient – measured along a horizontal surface – is positive $\frac{\partial T}{\partial x} > 0$ near the ground. So thermal wind: $\frac{\partial v_g}{\partial z} > 0$.

Above the level of the inversion the gradient may again reverse such that $\frac{\partial v_g}{\partial z} < 0$.

Near the ground frictional forces decrease the wind speed. This leads to the formation of a jet at the level of nocturnal inversion. The stability of the air (lack of mixing) below the inversion helps the jet to persist.

The thermal wind mechanism does not explain the super-geostrophic wind, however. It may on the other hand, work together with the inertial oscillation theory.

References cited:

Arritt, R. W., T. D. Rink, M. Segal, D. P. Todey, C. A. Clark, M. J. Mitchell, and K. M. Labas, 1997: The Great Plains Low-Level Jet during the Warm Season of 1993. *Mon. Wea. Rev.*, **125,** 2176-2192.

Beebe, R. G. and F. C. Bates, 1955: A mechanism for assisting in the release of convective instability. *Mon. Wea. Rev.*, **83,** 1-10.

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 the low-level jet. *Mon. Wea. Rev.*, **96,** 833-850.

Higgins, R. W., Y. Yao, E. S. Yarosh, J. E. Janowiak, and K. C. Mo, 1997: Influence of the Great Plains Low-Level Jet on Summertime Precipitation and Moisture Transport over the Central United States. *J. Clim.*, **10,** 481–507.

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

Maddox, R. A., 1983: Large-scale meteorological conditions associated with midlatitude mesoscale convective complexes. *Mon. Wea. Rev.*, **111,** 1475-1493.

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

Whiteman, C. D., X. Bian, and Shiyuan Zhong, 1997: Low-Level Jet Climatology from Enhanced Rawinsonde Observations at a Site in the Southern Great Plains. *J. Appl. Meteor.*, **36,** 1363–1376.

Zhong, S., J. D. Fast, and X. Bian, 1996: A Case Study of the Great Plains Low-Level Jet Using Wind Profiler Network Data and a High-Resolution Mesoscale Model. *Mon. Wea. Rev.*, **124,** 785–806.