A low Level Jet Observed by a Döppler Sodar during the International Sodar Intercomparison Experiment (ISIE)

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Abstract

The present authors have developed a phased array Döppler sodar and participated with it in the International Sodar Intercomparison Experiment (ISIE) at Boulder Atmospheric Observatory (BAO) in 1988. During the period of ISIE, a significant low-level jet (LLJ) was observed in the morning of September 18, 1988. The turbulent structure of an LLJ was analyzed using sodar observations as well as tower observations, and is summarized as follows; (1) Low frequency fluctuations (<0.002 Hz) increase in the time period of LLJ appearance. (2) The turbulent momentum flux in this frequency range shows divergence from the jet core in the developing stage and convergence toward the jet core in the decelerating stage. (3) This shows that turbulence acts as the resisting force to the development of an LLJ.

1. Introduction

A Döppler sodar is now recognized as a powerful tool of wind observation in the planetary boundary layer. Even though the development of new hardware and improved methods for data processing have continued, there still remains a need to verify the performance of sodars using comparisons with traditional sensors on a tall tower. The International Sodar Intercomparison Experiment (ISIE) was held at the Boulder Atmospheric Observatory (BAO) to assess sodar performance during the period September 6 to September 22, 1988 (Gaynor *et al.*, 1990).

The present authors have developed a phased array Döppler sodar with 5×5 horns using 1400 Hz sound signal, AR-400 (Ito *et al.*, 1989), as the next generation of the three-axis mono-static sodar

(Mitsuta & Uchida, 1985), and participated in ISIE. The results were satisfactory and are to be reported in another paper (Takehisa *et al.*, 1991).

During the period of ISIE, a significant low-level jet (LLJ) was observed on the morning of September 18, 1988. The results of wind profile and momentum flux analysis during this phenomenon are described in the present paper.

2. Instrumentations and site

The new phased array sodar (AR-400) has specifications as shown in Table 1. 5×5 horns are switched to form the vertical and slanting beams alternatively. One cycle of observation, directing vertical, north, east, south, west and then vertical again, is made every 20 sec. The five-beam data are processed to obtain three-dimensional wind components every 30 m in height assuming uniformity of wind

Table 1. System parameters of the wind profiling sodar.

Operating frequency	1400 Hz
Horn array	5 × 5
Maximum output power	1500 W (electric)
Antenna aperture	0.64 m ²
Zenith angle of steering beams	23°
Beam width	17°
Pulse length	100, 350 ms
Pulse repetition period	4, 8 sec
Range resolution	30 m
Döppler frequency estimation	FFT/Simple Homodyne Complex Covariance

within a beam spread of about 80 m in diameter at a height of 100 m.

As we have enough information in the five-beam method to measure three-dimensional wind components, it is possible to evaluate errors in wind estimation by the method developed by Strauch *et al.*, (1987). We assume uniformity of horizontal and vertical wind speed within the beam spread, and the vertical velocity to be represented by the value evaluated by the vertical beam. Errors in evaluating the horizontal wind component $(VAR(\delta V_x))^{1/2}$ can be written as follows,

$$VAR(\delta V_x) = VAR(\delta V_{rz}) \tan^2 \theta + VAR(\delta V_{rx}) \sec^2 \theta,$$

where δV_{rz} is the observational error of radial velocity measured by the vertical beam, δV_{rx} is that measured by the slanting beams, θ is elevation angle of the slanting beams and $VAR(X)$ is the variance of the value X . $(VAR(\delta V_{rz}))^{1/2} \tan \theta$ and $(VAR(\delta V_{rx}))^{1/2} \sec \theta$ are the errors caused by the assumption of wind uniformity within beam spread and the random error of radial velocity measurement. We can evaluate the two terms in the right-hand side of the equation from the observations of five radial velocities of the sodar. The errors estimated from the observational results during ISIE are 0.35 ms^{-1} at 75 m and 0.60 ms^{-1} at 300 m for horizontal wind component evaluation in an averaged wind speed of 5 ms^{-1} . The errors caused by the assumption of wind uniformity within beam spread area are 0.20 ms^{-1} at 75 m and 0.38 ms^{-1} at 300 m (Takehisa *et al.*, 1991).

The BAO is located at 105°W , 40°N at the foot of the Rocky Mountains as shown in Fig. 1. On the observation tower of 300 m height, wind, temperature and humidity sensors are installed at 10, 22, 50, 100, 150, 200, 250 and 300 m. The sodar was located about 650 m south of the tower.

3. Mean diurnal changes

During the ISIE, moderate fine days were Septem-

Fig. 1. Contour map of the area around the Boulder Atmospheric Observatory.

ber 7, 8 and 15 through 20. In this period, a low-level jet (LLJ) was seen on the morning of September 18. The time changes of air temperature and wind components observed at 10 and 150 m on the tower are shown in Figs. 2~4 comparing the day of the LLJ appearance (broken line) and other days (solid line). All of the data are shown as the averaged value of deviation from the value at 10 m at 12:00 MST of the day.

Temperature variations are almost the same in both cases. The amplitude of the temperature variation is smaller at higher levels and the phase is delayed one or two hours at the higher level. Wind velocity variations are quite different in both cases. On normal days, the westerly component starts to increase at sunset and shows its peak around 22:00 MST. This may be the down-slope wind of the Rocky Mountains as reported by Hahn (1981) or Blumen (1984). The southerly component decreases until sunset and then increases until sunrise. The southerly component is larger at lower levels than higher levels. On the morning of September 18, the

Fig. 2. Time changes of westerly wind speed at the height of 10 m, a) and 150 m, b), averaged over 7 days (solid lines) and for 17 to 18 September (dashed lines). Wind speeds are shown relative to the value at 10 m at 1200 MST.

Fig. 4. As in Fig. 3 except for temperature.

Fig. 3. As in Fig. 2 except for the southerly wind speed.

wind was significantly stronger than on other days at the higher level.

4. Structure of low level jet

Vertical profiles of 20 minutes averaged wind speed and direction from 04:00 to 08:40 MST September 18 are shown in Fig. 5. Before 04:40 MST, wind speed was about 5 ms^{-1} and from south, but the wind speed increased abruptly to 10 ms^{-1} at the height of 100 m forming a LLJ at 05:00 MST. The peak height was kept constant at about 100 m and the maximum wind was about 10 ms^{-1} . After sunrise (05:45) the jet core became a little higher and the wind speed increased rapidly until 06:00 MST, and remained high until 07:40 MST, when the jet became weak and entirely disappeared at 08:20 MST. The wind direction was almost SSW throughout the LLJ period. The wind shear is about -0.03 s^{-1} above the jet core and 0.05 to 0.06 s^{-1} below the core in the peak period.

The temperature profiles are shown in Fig. 6 together with sodar echo intensities for the same period. Before 04:40 MST, the surface inversion is located near ground level, but once the LLJ was formed the layer below the core became stable and the height of the LLJ core corresponded to the inversion top. The air temperature tended to increase in the air layer above the jet core or inversion top, and to decrease in the air layer below the jet core. After sunrise the surface inversion disappeared rapidly. The receiving power was a maximum at a little lower level than the jet core, or at the level of maximum temperature gradient. It is suggested that temper-

Fig. 5. The profiles of 20-minute averaged wind speed (solid lines) and wind direction (dashed lines) from 0400 MST to 0840 MST as observed on the BAO tower on September 18.

Fig. 6. 20-minute averaged temperature profiles as observed on the BAO tower and sodar echo intensities (horizontal black bars, arbitrary scale) from 0400 MST to 0840 MST on September 18.

Fig. 7. The spectra of the wind velocity component along the average wind direction (U) from 0310 MST to 0435 MST (dashed lines) and from 0545 MST to 0710 MST (solid lines) on September 18.

Fig. 8. As in Fig. 7 except for the vertical wind velocity component (W).

ature fluctuations show a maximum near the jet core level.

5. Turbulent characteristics as observed by a sodar

As explained before, the random errors of total velocity measurement of the sodar is estimated to be 0.35 ms^{-1} at 75 m height and 0.60 ms^{-1} at 300 m height. These errors may be small enough to use the instantaneous values of sodar wind measurement for turbulence analysis.

One cycle of the wind measurement of this sodar using the five-beam method needs 20 sec for a short-range measurement. The beam spread is about 80 m at 100 m height, in which wind is assumed to be uni-

form. The height resolution is 30 m. Three components of wind velocity are computed averaging two data for each component in one cycle of observation with the averaging volume and time mentioned above.

The power spectra of horizontal wind and vertical wind components in the periods before the LLJ (03:10~04:35) and during the LLJ (05:45~07:10) as observed by the sodar are shown in Figs. 7 and 8 for three heights, below, at, and above the jet core level (30, 120 or 180 and 240 m). As is clear from these figures, spectra are different during the time period of the LLJ appearance from those in earlier time periods. The spectral densities at low frequencies below 0.002 Hz, where there is an energy gap of the spectrum, shows larger values particularly near

Fig. 9. a) Momentum flux $\overline{u'w'}$ for $f < 0.002$ Hz fluctuations in the period from 0500 MST to 0600 MST on September 18. b) Momentum flux $\overline{u'w'}$ for $f < 0.002$ Hz from 0600 MST to 0740 MST on September 18. Arrows show the height of maximum wind velocity.

the jet core level during the LLJ period.

In the period of the LLJ appearance, the covariance of U and W in low frequency part also increases, even though the covariance in the higher frequency part remains constant and small throughout the day. This corresponds to the increase of power spectral density of wind turbulence in the frequency range lower than 0.002 Hz. It is suggested that turbulence in the frequency range lower than 0.002 Hz may be related to LLJ formation.

During the existence of the LLJ the covariance between U and W at frequencies lower than 0.002 Hz changes its sign at about 06:00 MST, the time of maximum jet wind speed at all heights. Moreover, the distribution of covariance with height shows divergence of momentum flux before 06:00 MST and convergence after that time at the jet core height, as shown in Fig. 9.

Before 06:00 MST or the time of maximum jet

Fig. 10. A hodograph of wind velocity at 150 m height from 1600 MST September 17 to 0900 MST September 18.

wind speed, the turbulent momentum flux is upward above 100 m, the height of jet core, and downward below that level. It shows the momentum divergence around the jet core. After 06:00 MST, the turbulent momentum flux changes its sign downward above and upward below the core at the height about 170 m. This is the remarkable results on the turbulent structure of LLJ.

6. Discussion

The mechanism of the LLJ that appears in the boundary layer in early morning has been identified as inertial oscillation of the air layer in the inversion layer (Blakadar, 1957, and Thorpe and Guymer, 1977). The inertial period of the BAO at 40°N is 18.5 hours. If the inertial oscillation starts at sunset (18:00), the peak will appear at 03:00 or 04:00 MST. The peak actually appeared at 06:00 MST near the time of sunrise. The hodograph of wind at 150 m is shown in Fig. 10. This may suggest an inertial oscillation starting from 21:00 MST with the peak at 06:20 MST. 21:00 MST is the starting time of the increase of the south-westerly component. A clear explanation of the LLJ mechanism could not be found. However, cooling of the great plain to the east of this point and the westward fast-moving sunrise heating front on the great plain may have close connection with this.

According to momentum flux measurements, in the developing stage of LLJ, momentum is lost from the jet core upward and downward to resist development, and after that momentum is converging to the jet core to resist slowing down of the jet. Forcing of the low-level jet is resisted by the environment and the true motive force must be found outside. Inertial motion may be the most probable source.

7. Conclusion

During the period of the International Sodar Intercomparison Experiment (ISIE), a significant low-level jet (LLJ) was observed on the morning of September 18, 1988. This LLJ was analyzed us-

ing sodar observations as well as tower observations. Turbulent structure of the LLJ is characterized by an increase of very low frequency fluctuations (< 0.002 Hz). Turbulent momentum flux as observed by a Döppler sodar in this frequency range showed momentum divergence from the jet core in the developing stage before the maximum core wind speed. Convergence toward the jet core was observed during the decelerating stage. This shows that turbulence acts as the resisting force to the development of the low-level jet.

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国際ソーダー比較観測（ISIE）の期間中に観測された低層ジェット（LLJ）について 片岡 毅

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開口合成ドップラーソーダを開発し、米国ボルダーで1988年に行われた国際比較観測（ISIE）に参加した。比較観測の期間中、1988年9月18日早朝に顕著な低層ジェット（LLJ）が出現したので、ドップラーソーダおよび気象観測鉄塔で得られたデータを基にLLJの乱流構造の解析を行った。結果は次に示すとおりである。(1) 0.002 Hzより低い低周波の変動がLLJの出現に伴い増加する。(2) この周波数帯域における乱流運動量フラックスは、LLJの成長過程では、ジェットの軸から発散しているのに対し、LLJの減衰過程においては、ジェットの軸に向い収束している。(3) これより、乱流運動はLLJの発達に対しては抵抗力として働いている。