DIURNAL VARIATIONS OF THE PLANETARY BOUNDARY LAYER OBSERVED WITH AN L-BAND CLEAR-AIR DOPPLER RADAR

(Research Note)

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Abstract. Based on continuous observations of the planetary boundary layer (PBL) with an L-band (1357.5 MHz) boundary-layer radar (BLR) at a hilly location in Japan, we have discovered that on clear days, a thin enhanced echo layer corresponding to the top of the PBL (or mixed layer) appeared at about 500 m height in the morning and ascended to about 1500 m in the afternoon. Strong upward velocities were observed below the echo layer (or inside the PBL), reaching 1500 m in the afternoon.

1. Introduction

The planetary boundary layer (PBL) is recognized as an important layer connecting the free atmosphere with the Earth's surface where almost all sources of energy, momentum and constituents in the Earth's atmosphere are to be found. Earlier observational studies of the PBL with aircraft, sodar, lidar, radiosondes and towers (see reviews of Stull, 1988; Garratt, 1992) are unsatisfactory due to their limited height coverage and resolution. Those observational difficulties are now being overcome by advances in radio probing techniques, called boundary-layer radars or profilers (Ecklund *et al.*, 1988, 1990; May and Wilczak, 1993).*

We have successfully developed a transportable L-band Doppler radar system (the Kyoto University Boundary-Layer Radar, hereafter the BLR) (Fukao *et al.*, 1995). This paper describes the first significant meteorological results obtained with this radar system on clear days at a hilly location in Japan.

* *Note added in proof:* A brief summary of our observations was presented at a domestic meeting in October 1992 and at several international meetings (Hashiguchi *et al.*, 1993a, b, c). After submitting this paper, we have noticed similar independent work by Angevine *et al.* (1994). They used a 915 MHz profiler on a plain in the U.S., whereas we used a 1357.5 MHz radar at a hilly location in Japan.

2. Kyoto University Boundary-Layer Radar (BLR)

The BLR used in this study was developed by the Radio Atmospheric Science Center (RASC) of Kyoto University in 1991 (Fukao *et al.*, 1995). It is a small and transportable radar operating at a frequency of 1357.5 MHz (L-band) with a peak transmitter power of 1 kW. The antennas consist of three parabolic antennas with diameters of 2 m, which are directed upward, northward and eastward with zenith angles of 15°. The radar provides vertical profiles of the three components of the wind velocity vector in the lower troposphere, including the PBL, with time and height resolutions of about 1 min and 100 m, respectively. The BLR was installed in December 1991 at the MU (Middle and Upper atmosphere) Observatory (34.85° N, 136.10° E, 385 m above sea level) located among small mountains in Shigaraki, Japan but the fetch is relatively open to the north towards Lake Biwa (671 km^2) about 30 km from the site.

The first continuous observations were conducted for four months during May–August 1992. In this period, the lowest observation height was about 500 m, but this has now been improved to about 300 m by reducing ground clutter effects (Hashiguchi *et al.*, 1995).

3. Diurnal Variations of Echo Intensity

Figure 1 shows a time-height cross-section of echo intensity observed with the BLR on clear days during 1–3 June 1992. Throughout this paper, height from the ground is used and the echo intensity is corrected by the square of the range. In this period, we found striking diurnal variations in the occurrence of strong echoes. A thin enhanced echo layer appeared in the morning (~08 LT) every day at about 500 m and ascended to about 1500 m in the afternoon (~14 LT). After 14 LT, the enhanced echo layer gradually disappeared.

The echo intensity obtained by an atmospheric radar is caused by non-uniformity of atmospheric refractivity. Since the PBL is well mixed by convection and turbulence, the echo intensity is expected to be very strong at the top of the PBL where both the temperature and humidity gradients become quite significant. Based on simultaneous radiosonde measurements at the radar site on clear days, we found that the height of the maximum echo intensity corresponded to the top of the clear daytime convective PBL (or mixed layer) defined by a virtual potential temperature gradient.*

The echo intensity is also dependent on the level of turbulence whose spatial scale is half a radar wavelength (~0.11 m). However, turbulence intensity estimated from the width of the Doppler spectra (Hocking, 1985) was highest inside the PBL where BLR echoes were not strongest. Therefore, we consider that the strong echo

* This feature and its diurnal variation are found also by Angevine *et al.* (1994) with their 915 MHz profiler.

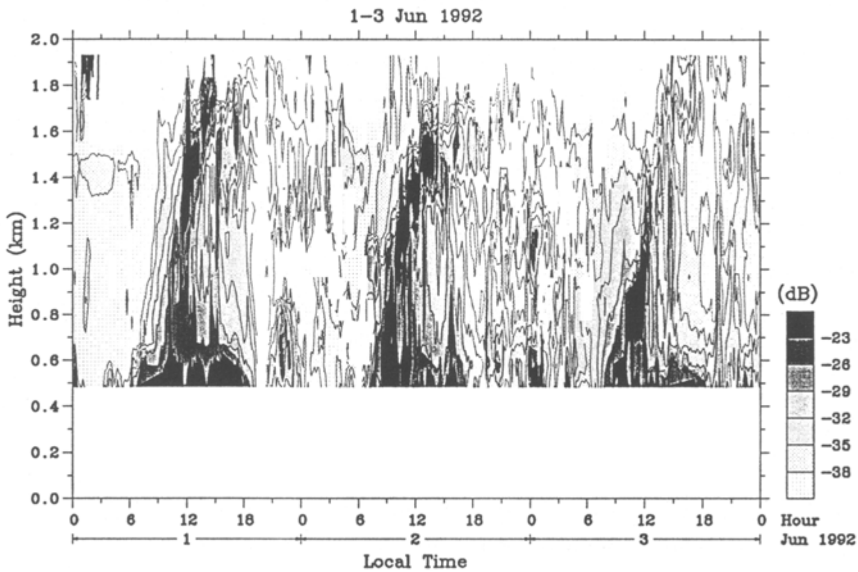

Fig. 1. Time-height cross-section of the BLR echo intensity averaged every 10 min for the eastward beam (azimuth = 90°, zenith = 15°) on clear days during 1–3 June 1992.

intensity is induced mainly by the temperature/humidity gradient at the top of the PBL, rather than by turbulence.

It must be noted that such remarkable diurnal PBL variations did not always occur on clear days. In the whole observational period of about four months at Shigaraki, they were limited to a few days each month, occurring in spells of two or three days.

4. Variations of Atmospheric Motion

Figure 2 shows diurnal variations of the three-dimensional wind velocity averaged during 1–3 June. Upward velocities much larger than the ascent speed of the echo layer ($\sim$0.07 m s^{-1}) were observed in the height range of 0.8–1.5 km at about 08 LT when the PBL was most rapidly growing. Also it is to be noted that northerly winds predominated at heights above 1 km. In fact in almost all cases when the remarkable diurnal variation of the enhanced echo layer was observed during May–August, a northerly wind predominated in the free atmosphere. Indeed on 4 June when a southerly wind became dominant, the diurnal variation was not remarkable in spite of the clear skies.

Figure 3 shows the monthly-mean diurnal variation of horizontal winds. There is little evidence for a mountain-valley circulation, and the horizontal wind vectors were almost always rotating clockwise with height as predicted in classical Ekman theory. These features are somewhat different from the earlier results of May and

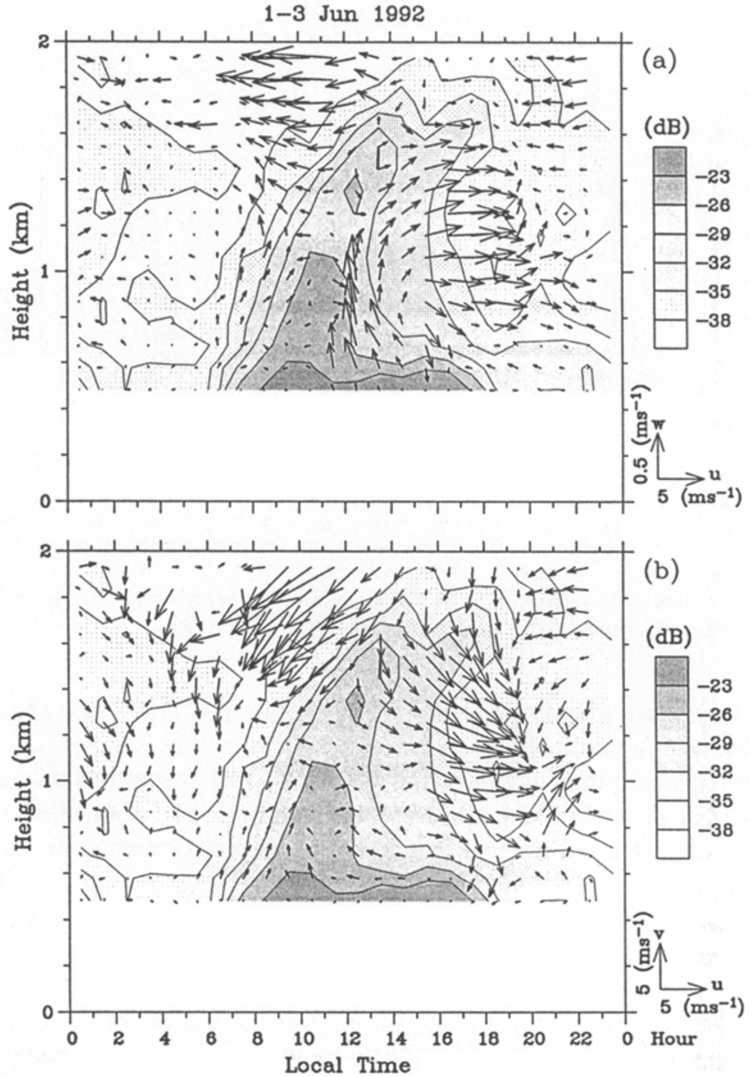

Fig. 2. Daily variation of (a) zonal-vertical and (b) zonal-meridional winds, averaged for three days during 1–3 June 1992. A vector directed upward in (a) represents rising air and in (b) a southerly wind.

Wilczak (1993) at Denver, U.S., which included a downslope circulation and a diurnal wind oscillation.

5. Discussion and Conclusion

We have found well marked PBL diurnal variations on the clear days that we studied in this paper. The observational evidence by the BLR was quite consistent

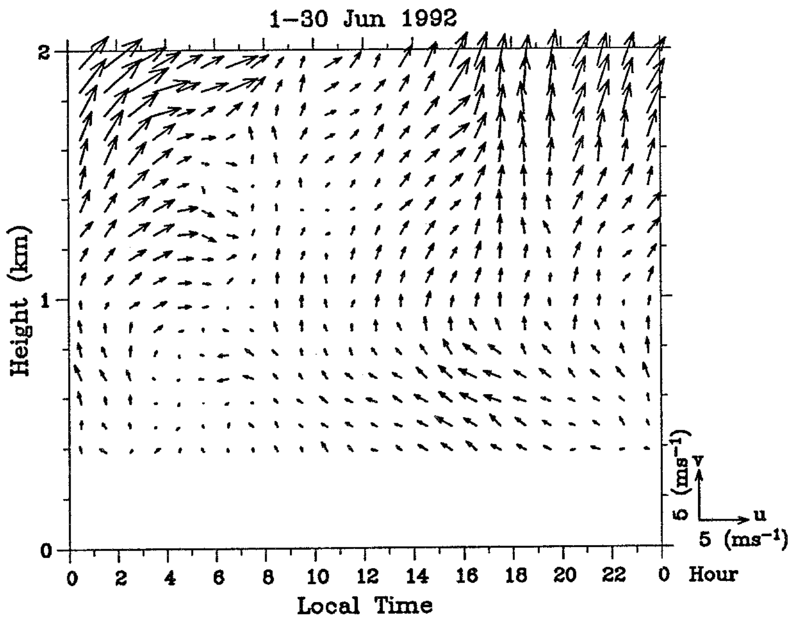

Fig. 3. Monthly-mean daily variation of horizontal wind in June 1992.

with the time evolution of the PBL calculated numerically by Yamada and Mellor (1975).* [Their calculations treated the PBL over a plain whereas the present BLR observations were conducted among small mountains.]

We have found from our BLR observations that a strong diurnal cycle can appear in the PBL (or mixed layer) even over hilly terrain, if the weather is fine and atmospheric conditions are suitable. The radar site of the present study is surrounded by small mountains, but there is a relatively open fetch to the north; Lake Biwa is located about 30 km north of the site. We believe that the diurnal variation may be smeared by orographic disturbances when the dominant larger-scale wind is not from the north. However, a detailed discussion of this hypothesis is beyond the scope of this paper.

Since the principal objective of this paper is to describe the usefulness of the L-band BLR and its first findings in the study of the PBL, we have not utilized the full capabilities of the BLR here. Variations of vertical wind, turbulence intensity and the height of the top of the PBL can be observed every minute, which was impossible with classical observation techniques. We believe that this time resolution will contribute to the elucidation of fine scale structure of the PBL.

* Angevine *et al.* (1994) also report similar diurnal variations observed in a managed pine forest, but they do not describe any larger-scale wind conditions necessary for the appearance of such variations.

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