FEATURES OF DUST DEVILS IN THE URBAN AREA DETECTED BY A 3-D SCANNING DOPPLER LIDAR

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Abstract

Using a three-dimensional scanning coherent Doppler lidar (3D-CDL), we conducted atmospheric boundary layer (ABL) observation in an urban area, Sapporo, Japan, from April of 2005 to June of 2007. During the period, we were able to detect, for the first time, in urban area more than one hundred "invisible dust devils" in 7 days. They were detected only in the daytime and under relatively weak wind conditions with superadiabatic lapse rate near the ground surface. Whenever they appeared, the "fish net" (or "spoke") pattern of wind fields in ABL scale was also detected by the 3D-CDL. Characteristics of relatively strong dust devils (more than $0.1s^{-1}$) are summarized as follows: diameter ranged from 30m - 120m, the maximum vorticity was $0.26s^{-1}$, and the number ratio of cyclonic to anti-cyclonic rotation was 2:1 on the average. Several vertical vortices were detected in sea-breeze front in other cases, which suggests that sea-breeze would play an important role in their formation.

Key words: Dust devil, Coherent structure, Doppler lidar

1. INTRODUCTION

Dust devils are small-scale vertical vortices, which often occur in convective boundary layers (CBLs) when the surface wind is weak in the daytime. Many studies have been conducted on observation of dust devils in flat terrain or desert [e.g. Sinclair 1964], because they are visualized by tracers of dust and debris. These particles, however, do not always mark dust devils [Hess and Spillane, 1990]. For example, MacPherson and Betts [1997] reported that invisible dust devils were detected over the boreal forest by aircraft measurements. The dust devil may be a “ubiquitous” phenomenon not only in flat terrain or desert but also in various types of surface (e.g. urban) in CBLs.

The purpose of this study is (1) to investigate coherent structures in the ABL through long-term observation period and comparing them with large eddy simulation (LES) results, (2) to clarify characteristics of dust devils in Sapporo, an urban area, and (3) to discuss sources of vorticity through the observation of environmental conditions and airflow structures in the ABL.

2. OBSERVATIONAL SETTING OF THE 3D-CDL AND DETECTION OF DUST DEVILS

The 3D-CDL was usually operated such that the radial resolution was 50m and the elevation angle of the Plane Position Indicator (PPI) scan was 2.2^{o}, which is the lowest elevation to observe almost all directions without being blocked by any obstacles. The Range Height Indicator (RHI) scan was made along the predominant wind direction (NNW-ly) in the observation area. The scanning speed was $4.5^{o}\,s^{-1}$, so that complete PPI and RHI scans required ~80s and 40s, respectively. The azimuthal resolution was about 1.2^{o}, which results in space resolution of 92 m at 4.4 km range. The 3D-CDL was installed at 28 m above ground level (AGL) (40m ASL), and inner and outer circumference heights in a PPI scan with elevation angle 2.2^{o} are 43m and 197m AGL, respectively.

Dust devils in a PPI scan was obtained by detecting a pair of maximum and minimum Doppler velocities, and applying them to Rankine combine vortex model [Suzuki et al., 2008]. The vorticity of a dust devil is estimated from $2\Delta V/D$, where ΔV is the difference between maximum and minimum Doppler velocities, and D is the distance between them, which is assumed to be a core size of a dust devil in this paper [Bluestein et al., 2004].

3. LES EXPERIMENTAL DESIGN

The LES model by Nakanishi [2000] without moisture is used. The subgrid-scale turbulence follows a two part model of Sullivan et al. [1994] except that the turbulent kinetic energy is given diagnostically. The vertical velocity is set to zero at the ground surface and top boundary. The lower boundary conditions are given in terms of subgrid vertical fluxes. A constant heat flux of 0.24 Kms^{-1} is continuously supplied from the ground surface as thermal forcing. The momentum flux is determined from Monin-Obukhov similarity theory with a roughness length of 0.38 m for momentum. Periodic conditions are adopted at the lateral boundaries. The computational domain is divided into 177x177 grid boxes horizontally and 101 layers vertically. The grid spacing is 50 m in the horizontal direction and 25 m in the vertical direction.

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The atmosphere is initialized with a potential temperature of 293.15 K at the surface, a neutral stratification below a height of 600m, a strong capping inversion (0.01 K m^{-1}) from 600 m to 800 m, and a moderately stable stratification (0.004Km^{-1}) above 800m. The SW-ly geostrophic wind of 1.5 m s^{-1} is initially given throughout the whole domain. The simulation is run for 1 hour after small random perturbations are added to all velocity components.

4. RESULTS

4-1 Coherent structures

Figure 1 shows a comparison between Doppler velocity and radial convergence obtained from 3D-CDL observation and those from LES as would be observed from the centre of the computational domain. The LES results are similar to the observation results. The pattern of updraft regions in Fig. 1c seems to be the "fish net". Radial convergence of Doppler velocity in the low elevation angle could correspond to an updraft (Fig. 1c). Therefore the observed radial convergence in Fig. 1d is roughly considered to show the existence of the "fish net".

The 3D-CDL observation in Sapporo started in May of 2004. Various kinds of atmospheric phenomena (e.g. thermals, fish nets and streaks) in the ABL were reported by Fujiyoshi et al. [2005]. The observation results showed that the "fish net" appeared under relatively weak wind (< ~2 m s^{-1} at 59.5 m AGL at the Sapporo District Meteorological Observatory tower, located ~2 km SSW from the 3D-CDL site) in the daytime on fine days. On the other hand, "streak" appeared under relatively strong wind (> ~5 m s^{-1}) in any weather and relatively weak wind (< ~5 m s^{-1}) in the early morning. LES studies suggest that dust devils form within the "fish nets" in the CBL with calm wind [Kanak et al., 2000].

In order to detect dust devils from the 3D-CDL data, we selected days when the "fish net" was found during an analyzed period of April-June 2005 and October 2006-June 2007.

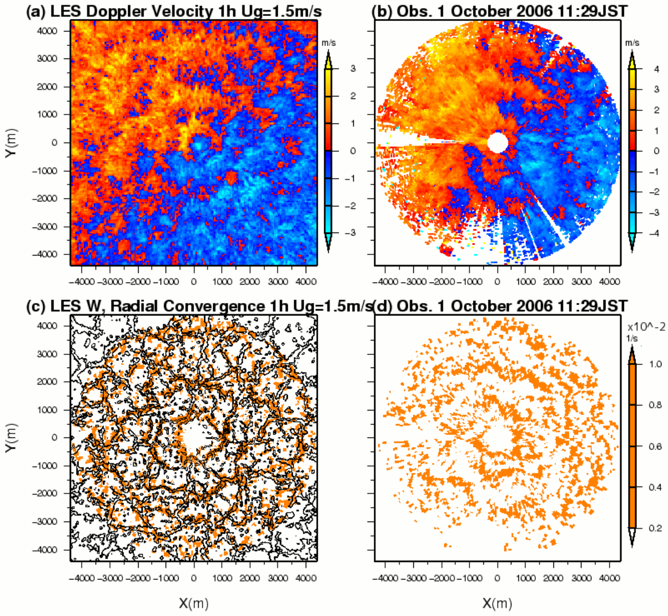

Fig. 1. A comparison of coherent structures from LES and 3D-CDL. (a) LES of Doppler velocity at elevation angle 2.2° in PPI scan after 1 hour from the initial time, (b) Observation of Doppler velocity at elevation angle 2.2° in PPI scan at 11:29 on 1 October of 2006, (c) Same as in (a) but for radial convergence (shade) and updraft region (contour value is 0.2ms^{-1}), (d) Same as in (b) but for radial convergence.

4-2 Detection of dust devils

Many dust devils were detected in 7 days of the analyzed period. Figure 2 shows a representative sample of a Doppler velocity field and a dust devil (maximum vertical vorticity case) detected from a PPI scan at 09:18 Japan Standard Time (JST) on 24 June 2005. The pattern of Fig. 2a is similar to that of Fig. 1b. Figure 2b shows that the Doppler velocity field around "dust devil A" shown in Fig. 2a corresponds well to Rankine combine vortex pattern. It rotated cyclonically with a diameter of 52 m and a vorticity of 0.19 s^{-1}. The maximum and minimum Doppler velocities of "dust devil A" were 3.5 ms^{-1} and -1.4 ms^{-1}, respectively (Fig. 2c). The distribution of its tangential Doppler velocity (L1-L2 line in Fig. 2b) is nearly the same as that of a Rankine combine vortex model. The S/N tends to be weak-echo in the vorticity core, which is similar to the reflectivity structure of a radar observation [Bluestein et al., 2004].

Table 1 shows the summary of the characteristics of relatively strong dust devils (more than 0.1s^{-1}) in 7 days of the analyzed period. These characteristics were arranged according to the diameter and maximum absolute value of vorticity. For the 7 days, 50 strong dust devils were detected, and the diameter of their core ranged between 30-120 m and the maximum vorticity between 0.15-0.26 s^{-1}. 32 of 50 dust devils were cyclonic, while the others were anticyclonic. These dust devils occurred when the season was either spring or summer, the wind was relatively weak (<2.2 ms^{-1}) in the daytime, and the depth z_i of the ABL was relatively large (>650m). The vertical profile of virtual potential temperature on these days showed a moderately superadiabatic lapse rate of 1.1-2.0×10^{-2} K m^{-1} from 1.5 m to ~100 m.

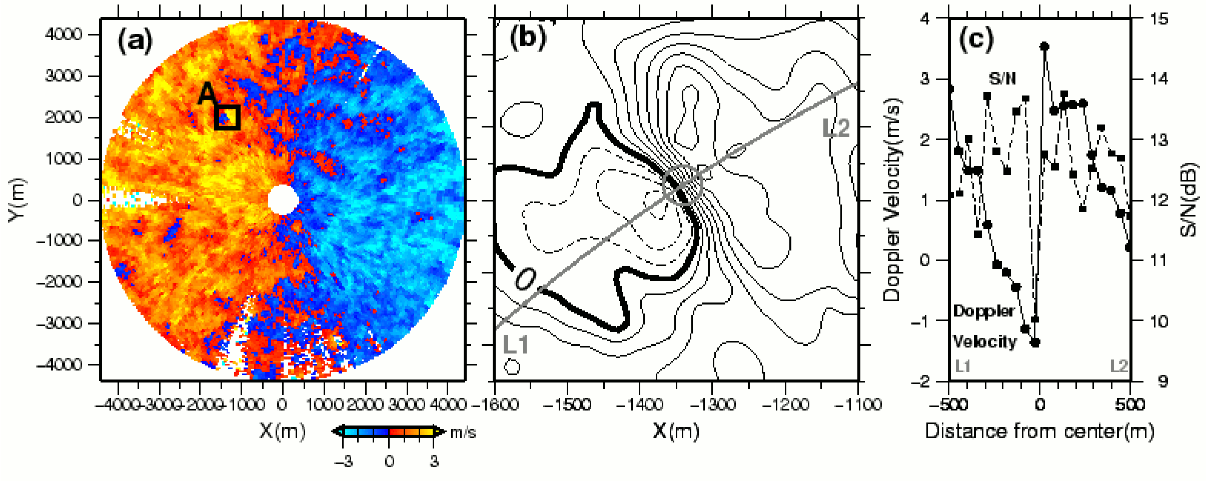

Fig. 2. (a) Doppler velocity at elevation angle 2.2° in PPI scan at 09:18JST on 24 June 2005. The square box enclosing “dust devil A” is expanded as shown in (b). (b) Detailed Doppler velocity of dust devil A. Contour intervals are 0.5m/s. Gray circle and dot indicate the diameter and center of dust devil A respectively, while its tangential direction is represented by L1-L2 line. (c) Tangential variations of Doppler velocity and S/N for “dust devil A” on L1-L2 line.

Table 1. Some characteristics of the observed dust devils. z_i is estimated as the height at which the negative gradient of S/N is maximum. For 3 of 7 days, virtual potential temperature (VPT) from soundings at a launching time (08:30 JST), around which the dust devil formed, is available, so that VPT lapse rate is also shown as a reference.

	Time (JST)	Diameter (m)	Maximum Vorticity (s^{-1})	Rotation direction +/−	Vectorial Mean Wind (ms^{-1})	z_i (m)	z_i At 08:30 JST (m)	VPT Lapse rate at 08:30JST ($x10^{-2}Km^{-1}$)	Total Number
2005/5/25	09:29-10:11	30-110	0.25	11/3	0.3	1150	1270	2	14
2007/6/22	11:48-12:33	70-120	0.21	6/2	1	950	-	-	8
2005/7/17	10:58-11:41	30-120	0.26	7/3	1.1	950	-	-	10
2005/4/14	12:47-13:22	50-90	0.19	1/3	1.1	1150	-	-	4
2005/6/24	09:01-09:43	50-100	0.19	3/1	1.3	900	660	1.5	4
2005/4/24	14:04-14:46	50-90	0.15	1/3	2	650	-	-	4
2005/6/1	09:01-09:43	40-80	0.17	3/3	2.2	750	660	1.1	6
Total		30-120	0.15-0.25	32/18	0.3-2.2	650-1150	660-1270	1.1-2.0	50

5. DISCUSSION

We focus on meteorological environmental conditions and airflow structures in the ABL to discuss sources of vorticity. The environmental conditions in dust devil events are characterized by a relatively weak wind and a relatively deep z_i. A moderately superadiabatic lapse rate from 1.5m to 100m is a typical CBL situation that induces large buoyancy. This is consistent with previous observational studies of dust devils in flat terrain or desert. These conditions as discussed by Hess and Spillane [1990], suggest that a stability parameter ($-z_i/L$) was large qualitatively, where L is the Obukhov length.

Figure 2a shows that the Doppler velocity field is similar to the “fish net” pattern. It is consistent with Kanak et al. [2000] who suggested that a source of vorticity in no mean wind and wind shear is a tilting of horizontal vorticity associated with the “fish net” in a flat terrain. It is quite likely that dust devils occur within the “fish net” which appears under weak wind and large sensible heat conditions in various types of ground surface.

Observational studies suggested that there are great varieties in the sources of dust devils. Hess and Spillane [1990] showed that some dust devils occurred along the edge of a density current, which may be a result of rolling up a vortex sheet [Barcilon and Drazin, 1972]. We also detected several small vertical vortices along the sea-breeze front (Fig. 3). In the next study, we plan to examine cases of airflow structures different from "fish net" and to discuss sources of such vertical vortices.

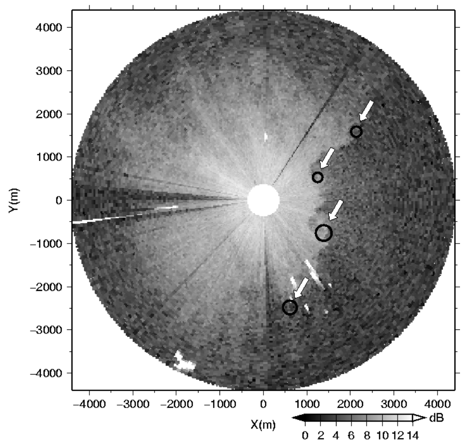

Fig. 3. Dust devils in a sea-breeze front. S/N at elevation angle 2.2° in PPI scan. Black circles and white arrows indicate detected dust devils.

6. CONCLUSION

We detected 50 dust devils in seven days using the 3-D CDL in Sapporo in the daytime. The characteristics of the detected dust devils were as follows: the diameter ranged between 30 and 120 m, maximum vorticity ranged between 0.15 and 0.26 s^{-1}, and 32 dust devils rotated cyclonically while 18 anticyclonically. Meteorological environments in the seven days were in the conditions of a relatively weak wind and a relatively deep z_i. This is the first observation that invisible dust devils and "fish net" patterns were simultaneously detected by the 3-D CDL in an urban area.

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