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Citation	SOLA, 8, 25-28 https://doi.org/10.2151/sola.2012-007
Issue Date	2012-04-01
Doc URL	https://hdl.handle.net/2115/49502
Type	journal article
File Information	Sola8_25-28.pdf

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Observed Effect of Mesoscale Vertical Vorticity on Rotation Sense of Dust Devil-Like Vortices in an Urban Area

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Abstract

Dust devil-like vortices were detected by a three-dimensional scanning coherent Doppler lidar (3D-CDL) in an urban area of Sapporo, Japan, from April 2005 to July 2007. A total of 57 strong, dust devil-like vortices with vertical vorticity exceeding 0.1 s^{-1} were detected in 8 days of the observation period and were associated with a convective cell (fish net) pattern of wind fields detected by the 3D-CDL. The observed vortices had both rotation senses for 7 days. However, all of 7 dust devil-like vortices were cyclonic on 4 October 2006 when cyclonic mesoscale circulation with 4.5×10^{-4} s^{-1} in vertical vorticity existed over the 3D-CDL observation area. This result is the observed evidence that mesoscale circulation affects rotation sense of vortices.

1. Introduction

Dust devils are small-scale vertical vortices marked by entrained dust and sand. Whether these vortices exhibit a preferred sense of rotation has been a controversial issue (e.g., Durward 1931; Williams 1948; Sinclair 1965; Carroll and Ryan 1970; Fitzjarrald 1973). Balme and Greeley (2006) summarised previous measurements of rotation sense in flat or desert areas and showed that both rotation senses appeared equally (see their Table 2). Sinclair (1965), however, reported that the largest dust devils (diameter > 45 m) tend toward cyclonic rotation.

To understand the source of vorticity, it is important to understand how the rotation sense of a dust devil is determined. Carroll and Ryan (1970) stated that the observed rotation of a well-developed dust devil should reflect the sense of atmospheric vertical vorticity at the time and place of formation. Possible sources of vorticity range from the earth's rotation (Durward 1931; Brooks 1960) through mesoscale circulation, such as terrain effects and natural and man-made obstacles, to the wakes of running animals (Ives 1947). Several numerical studies without the sources suggest that vertical vorticity of dust devils can be generated from convective cell circulation (e.g., Kanak et al. 2000). Recently, Ito et al. (2011) performed a LES (Large Eddy Simulation) with initial ambient vertical vorticity with O ($+10^{-3}$ s^{-1}) and showed that the ambient rotation significantly affects the rotational direction of the vortices. So far, however, no simultaneous observation of mesoscale circulations and dust devils has been conducted to clarify whether mesoscale circulations really affect rotation sense of dust devils.

Using a three-dimensional scanning coherent Doppler lidar (3D-CDL), we detected many dust devil-like vortices in Sapporo, an urban area, from April 2005 to July 2007 (Fujiwara et al. 2011). A total of 50 strong vortices were detected over a total of 7 days during the period of observation. More than 60% of the vortices were cyclonic, and the rest were anticyclonic. Of note is that all seven of the vortices observed on the 4 October 2006 were cyclonic. The purpose of this study was to investigate the reason that only cyclonic vortices formed on that day.

A brief description of the observational setting of the 3D-CDL is stated in Section 2. Characteristics of vortices and flow structure in the atmospheric boundary layer (ABL) are contained in Section 3. Discussion on preference for cyclonic rotation and conclusions are given in Section 4.

2. Observational setting of the 3D-CDL and detection of dust devils

The 3D-CDL was installed on the roof of the Creative Research Institute of Hokkaido University, Sapporo, 28 m above ground level (AGL). The area covered by the 3D-CDL includes tall buildings in its southern part and low residential buildings in the northern part (Fig. 1c). The detection range of the 3D-CDL was 0.4−4.4 km with 50-m resolution. The azimuthal resolution is 1.2° which results in a spatial resolution of 9−92 m at a range of 0.4−4.4 km. The 3D-CDL performed plane position indicator (PPI) scans at elevation angles of 2.2° and range height indicator (RHI) scans along the predominant northwesterly wind direction at a rate of 4.5° s^{-1}. From a RHI scan taken by the 3D-CDL, the height of ABL (z_i) was determined by locating the height of the maximum negative gradient in its profile (Fujiwara et al. 2011).

Using the method presented by Suzuki et al. (2008), dust devil-like vortices in a PPI scan were obtained by detecting a pair of maximum and minimum Doppler velocities, and applying them to Rankine combined vortex model (detailed explanation is reported in Fujiwara et al. 2011). The distance between maximum and minimum Doppler velocities (D) is defined as the deduced core diameter of each vortex. Vertical vorticity (ζ) is estimated from $2\Delta V/D$, where ΔV is the difference between the receding and approaching extrema in the vortex signature. Fujiwara et al. (2011) estimated the influence of the spatial resolution of the 3D-CDL on the deduced diameter and vorticity of dust devil-like vortices; when the true diameter was 30 m, the deduced diameter and vorticity ranged from 70 to 300% and from 10 to 67%.

We used Sapporo City Multi-sensor (MULTI) network data over Ishikari Plain, Hokkaido, Japan, to investigate distributions of surface temperature and wind around the 3D-CDL observational area (Fig. 1b). Air temperature, wind velocity, and wind direction were measured by sensors mounted on a 5-m pole and automatically recorded every 10-min.

3. Results

Table 1 summarises the physical characteristics of detected dust devil-like vortices. Over a 7-minute period from 12:24 to 12:31 Japan Standard Time (JST) on 4 October 2006, a total of seven strong dust devil-like vortices (vertical vorticity exceeding 0.1 s^{-1}) were detected. Their core diameter ranged from 40 to 110 m, and maximum vorticity was 0.25 s^{-1}. They were detected in the daytime and under weak wind conditions (0.8 m s^{-1} at 59.5 m AGL at the Sapporo District Meteorological Observatory (SDMO)) with a deep boundary layer height (1050 m). These

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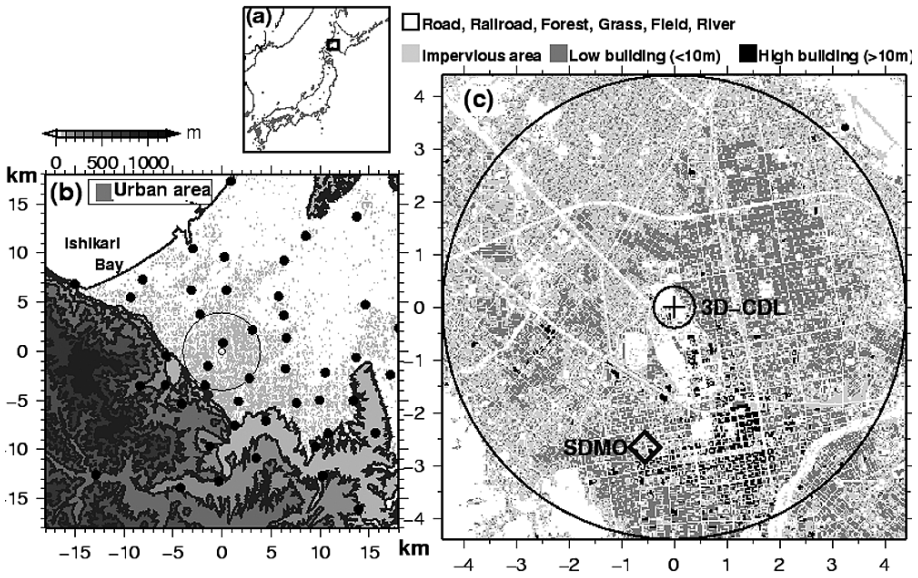

Fig. 1. (a) Location of the 3D-CDL observation area indicated by square. (b) Detailed topographic map of the observational area. Grey contour lines indicate the topography at 0 m, 50 m, 100 m, 200 m, 400 m, 600 m, 800 m, and 1000 m. The 3D-CDL site and its observational area are indicated by small and large circles, respectively. Black dots indicate the location of MULTI stations. (c) Detailed information of land around the 3D-CDL observational area, showing the locations of the 3D-CDL and Sapporo District Meteorological Observatory (SDMO).

physical characteristics and environmental conditions are similar to those observed in flat areas (e.g., Sinclair 1969) and urban areas (Fujiwara et al. 2011). However, they are different from previous studies because all showed cyclonic rotation.

The Doppler velocity fields around the strongest dust devil-like vortex A (Fig. 2b) have a similar structure to those of the Rankine combined vortex model. The deduced core diameter and the vertical vorticity were estimated to be 110 m and 0.25 s^{-1}, respectively. The pattern of the Doppler velocity field (Fig. 2a) was similar to the cellular convective ("fish net") pattern (see Stull 1988; Fujiwara et al. 2011). This feature is similar to previous observations (Fujiwara et al. 2011) and LES results (e.g., Kanak et al. 2000; Kanak 2005; Kanak 2008; Ohno and Takemi 2010; Ito et al. 2010; Ito et al. 2011; Raasch and Franke 2011). However, the wind velocity in the eastern area, about 4 m s^{-1}, was stronger than that in all other areas.

Heat-island circulation is expected to have been existed in the urban area of Sapporo in daytime on October 2006. Figure 3 shows the horizontal distribution of surface air temperature and wind vector determined by MULTI at 12:30 JST. Surface wind direction was northwesterly in the southwestern region of the 3D-CDL observation area; northerly in the northwestern region; and southeasterly in the northeastern region. Valley winds were present at the areas close to the mountains, and a sea-breeze front existed along the coast, as shown in Fig. 3. The location of the sea-breeze front was estimated using the time when the wind direction changed from offshore to onshore and when the temperature dropped at successive MULTI network stations. Surface air temperatures in the central part of the city were higher than those in the surrounding area at 12:30 JST. The urban surface temperature excess (ΔT) was defined as the difference between the mean temperature of four suburban stations (S1, S2, S3, S4) and that of four urban stations (U1, U2, U3, U4). At 12:30 JST, ΔT was about 1.1°C. Fujibe and Asai (1980) reported that a cyclonically converging flow associated with the heat island is seen around the urban area of Tokyo for ΔT = 1.3°C.

Figure 4a shows the horizontal distribution of vertical vorticity and surface-wind vectors interpolated to a 2 × 2-km horizontal grid spacing (the weighting function of interpolation method is inversely proportional to the square of the distance from grid to

Table 1. Physical characteristics of the dust devil-like vortices and corresponding environmental conditions.

	Time (JST)	Diameter (m)	Maximum Vorticity (s^{-1})	Rotation Direction +/−	Vectorial Mean Wind (m s^{-1})	z_i (m)	Ambient Vertical Vorticity (× 10^{-4} s^{-1})	ΔT (degree)	Heat island circulation	Total Number
14 Apr. 2005	1247−1322	50−90	0.19	1/3	1.1	1150	1.0	0.7	○	4
24 Apr. 2005	1404−1446	50−90	0.15	1/3	2	650	1.0	0.4		4
25 May 2005	0929−1011	30−110	0.26	11/3	0.3	1150	3.0	0.6	○	14
1 Jun. 2005	0901−0943	40−80	0.17	3/3	2.2	750	0.5	0.2		6
24 Jun. 2005	0901−0943	50−100	0.19	3/1	1.3	900	1.0	1.6	○	4
17 Jul. 2005	1058−1141	30−120	0.26	7/3	1.1	950	1.0	1.4	○	10
22 Jun. 2007	1148−1233	70−120	0.21	6/2	1	950	1.0	1.0	○	8
Fujiwara et al. (2011) Total		30−120	0.15−0.26	32/18	0.3−2.2	650−1150	1.0−3.0	0.2−1.6		50
4 Oct. 2006	1224−1231	40−110	0.25	7/0	0.8	1050	4.5	1.1	○	7

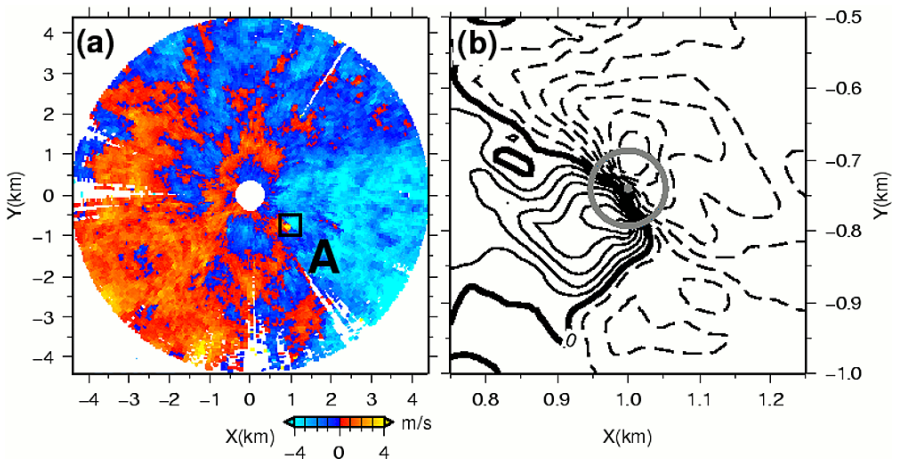

Fig. 2. (a) Doppler velocity at elevation angle 2.2° in PPI scan and detected Vortex A at 12:26 JST on 4 October 2006. (b) Close-up view of the Doppler velocity for Vortex A. The contour interval is 1 m s^{-1}. Thick solid lines indicate a zero value, and thin solid (dotted) lines show positive (negative) values. The deduced core diameter of the vortex is shown by a grey circle.

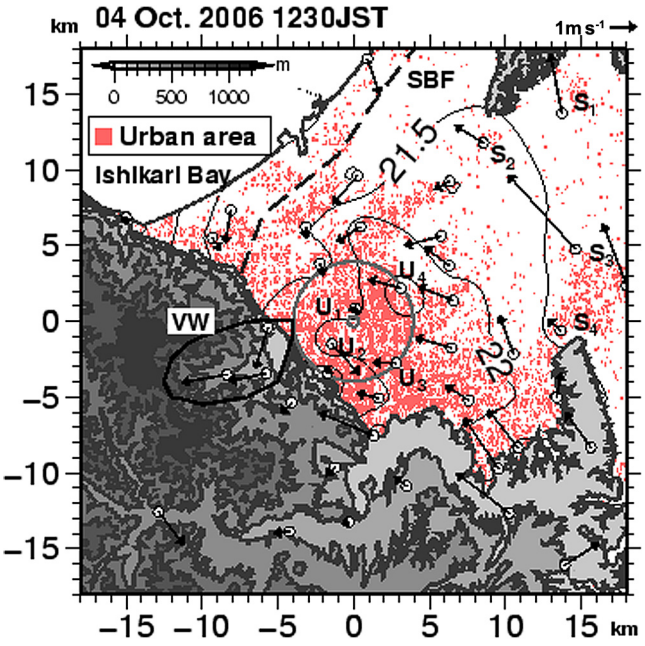

Fig. 3. Horizontal distribution of air temperature (contour line) and wind vector of MULTI at 12:30 JST on 4 October 2006. A grey circle indicates the observational area of the 3D-CDL. The dashed line and solid closed curve indicate the sea-breeze front (SBF) and the valley wind (VW), respectively.

MULTI station (Nakai 1982)). A cyclonic flow is evident, with a wind speed of about 1 m s^{-1} within the 3D-CDL observation area. Distribution of vertical vorticity and horizontal convergence (not shown) were calculated from interpolated wind data. The vertical vorticity and the horizontal convergence were of magnitude 4.5×10^{-4} s^{-1} and 5×10^{-4} s^{-1}, respectively. Figure 4b shows the Doppler velocity field averaged from 12:24 to 12:31 JST and the movement of detected vortices. It is to be noted that the vortices generally moved parallel to the ambient wind direction.

4. Discussion and conclusions

3D-CDL observations clearly show that all of rotation sense of vortices was cyclonic when a cyclonically converging flow associated with mesoscale circulation existed around the urban area of Sapporo on 4 October 2006. These features were also observed on 25 May 2005, when many of the detected vortices were also cyclonic (see Table 1). Therefore, our observational results support the results of the LES study performed by Ito et al. (2011). When cyclonic vortices were detected, a cyclonic mesoscale circulation was found to exist over the 3D-CDL observational area, and the urban surface-temperature excess increased. However, the observed vertical vorticity (4.5×10^{-4} s^{-1}) was much larger than that observed in the Tokyo metropolitan area (5×10^{-5} s^{-1}) (Fujibe and Asai 1980). We analysed surface wind and temperature using the MULTI network around the 3D-CDL observation area and found a heat-island-like circulation in six cases (14 April 2005, 25 May 2005, 24 June 2005, 17 July 2005, 4 October 2006, and 22 June 2007) (Table 1). However, values of the ambient vertical vorticity were weak (less than 1.0×10^{-4} s^{-1}) on 4 days (14 April 2005, 24 June 2005, 17 July 2005, and 22 June 2007). Furthermore, the relationship between ΔT and the ambient vertical vorticity was not clear, as shown in Table 1. These facts suggest that it is not only the heat-island circulation that would intensify the ambient mesoscale circulation in Sapporo but also such things as the sea breeze and valley winds. Moreover, we found that the majority of dust devil-like vortices developing along the sea-breeze front were cyclonic, the same direction of rotation as the vorticity associated with the sea-breeze front. This will be reported in more detail in an another paper.

Acknowledgements

Data from the Sapporo City Multi-sensor network was provided by Sapporo city and the Sapporo Information Network. Japan Meteorological Agency and the Geographical Survey Inst. provided wind, and hybrid land-cover data, respectively. We express our thanks to O. Suzuki of Met. Res. Inst. of Japan for permitting us to use his vortex detection program. We also appreciate the helpful discussions with Dr. M. Kawashima and Prof. T. Watanabe of Inst. Low Temp. Sci., Hokkaido Univ., and Prof. M. Nakanishi of the National Defense Academy of Japan. We wish to thank Dr. M. Yoshizaki and two anonymous reviewers for their helping comments.

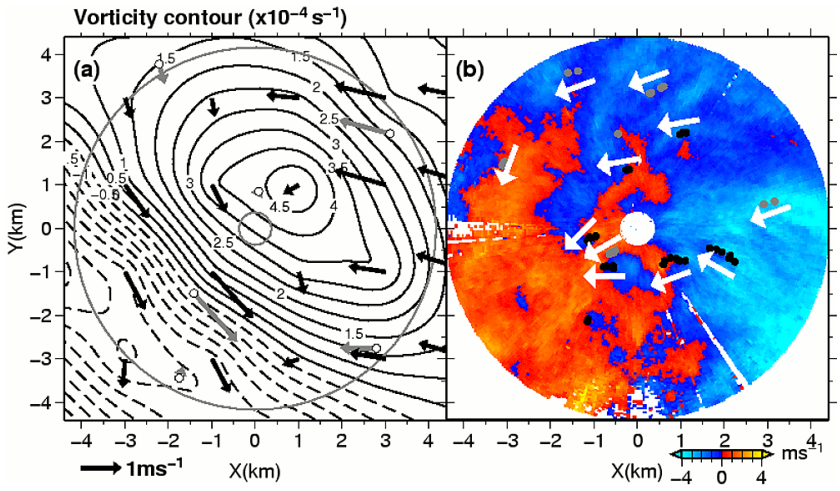

Fig. 4. (a) Wind vector at MULTI stations (grey), interpolated wind vector (black), and distribution of vertical vorticity of the flow (contour; $\times 10^{-4}$ s^{-1}) calculated from interpolated wind vector around the 3D-CDL observation area at 12:30 JST on 4 October 2006. (b) Distribution of averaged Doppler velocity at elevation angle 2.2° in a PPI scan from 12:24 to 12:31 JST and movement of detected dust devil-like vortices. Black and grey dots indicate relatively strong (maximum vorticity more than 0.1 s^{-1}) and weak (maximum vorticity less than 0.1 s^{-1}) vortices, respectively. White arrows indicate movement of vortices.

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Manuscript received 25 January 2012, accepted 8 March 2012
SOLA: http://www.jstage.jst.go.jp/browse/sola