Low-Level Wind Shear Induced by Horizontal Roll Vortices at Narita International Airport, Japan

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Abstract

Aircraft landing and taking off at Narita International Airport in Japan frequently report low-level wind shear (LLWS), which is a local variation in the wind vector, and turbulence when the prevailing wind is southwesterly, which is crosswind to the runway. On 20 June 2012, just before touchdown, an arriving aircraft at this airport encountered LLWS that consisted of a sudden change in the wind vector from a headwind component of 5 knots (2.6 m s$^{-1}$) to a tailwind component of 10 knots (5.1 m s$^{-1}$). This caused a rather hard landing. As the aircraft approached, none of cumulonimbus clouds, fronts, or wind shear lines were observed around the airport. Further analysis of the data measured by the landing aircraft and observations made by the Doppler lidar revealed that the LLWS was caused by horizontal roll vortices that developed in the atmospheric boundary layer (ABL) over the Shimofusa tableland surrounding the airport. The axes of these horizontal roll vortices were nearly parallel to the mean wind direction, while their horizontal and vertical scales were approximately 800 m and 500 m, respectively.

In our present study, we demonstrate that the existence of such horizontal roll vortices that cause LLWS can be effectively detected by a single Doppler lidar that utilizes backscattering from aerosols.

Although the LLWS associated with horizontal roll vortices has a smaller magnitude than those caused by a microburst, gust front, or front, landing aircraft often encounter these horizontal roll vortices just before touchdown with a much higher probability than other phenomena since horizontal roll vortices occur at a horizontal spacing of approximately 800 m over a wide area during the daytime hours of a clear day.

Keywords atmospheric boundary layer; horizontal roll vortices; low-level wind shear; Doppler lidar; Narita International Airport


1. Introduction

At approximately 0422 UTC (1322 LST) on 20 June 2012, an arriving aircraft encountered low-level wind shear (LLWS) that caused a sudden airspeed loss of 15 knots (7.7 m s$^{-1}$) after passing the threshold of the runway at Narita International Airport (hereafter, Narita Airport) in Japan (Yoshino and Sakamoto 2013). No convective or precipitating clouds, including cumulonimbus, were observed at the airport during the approach and landing, thereby suggesting that the cause of this LLWS was neither a wet microburst nor a gust front. Further, the amount of cloud observed in the atmospheric boundary layer (ABL) was only $1/8$. And the routine aeronautical meteorological observation at 0430 UTC reported that the surface wind measured by an anemometer on runway 34L was southwesterly, which is nearly perpendicular to the runway; this surface wind was measured to be 16 knots (8.2 m s$^{-1}$) with gusts reaching 29 knots (14.9 m s$^{-1}$).
m s$^{-1}$). Finally, Doppler lidar observations showed that within 15 km of the final approach course and runway, several features of organized horizontal roll vortices (e.g., Wurman and Winslow 1998; Christian and Wakimoto 1989), which are accompanied by alternating high- and low-speed wind bands oriented nearly parallel to the mean flow and the flows perpendicular to the mean flow, were present. Therefore, this case was examined with the hypothesis that the LLWS encountered by the landing aircraft was closely related to horizontal roll vortices. Note that horizontal roll vortices not accompanied by clouds have not been well recognized as a major cause of LLWS that affect low-level aircraft maneuvering. The primary objective of this study is therefore to reveal the existence and structures of horizontal roll vortices that were not visualized as cloud streets but induced LLWS in a dry ABL.

LLWS is a local variation of the wind vector that causes remarkable airspeed changes of an aircraft, including divergence and convergence at low altitudes below 1600 ft (Tabata and Fujibe 2010). In particular, when an aircraft flies at low airspeed at low altitudes during both landing and takeoff, a significant loss in airspeed due to LLWS, such as sudden transitions from a headwind to a tailwind, could cause a stall.

Although LLWS events caused by microbursts or gust fronts associated with cumulonimbus, fronts, and topographies are well known throughout the aviation community, those induced by horizontal roll vortices have never been discussed as a cause of LLWS to our knowledge.

When general winds prevail, horizontal roll vortices occur over oceans or lakes during cold air outbreaks (Walter 1980; Kelly 1982, 1984) and over land heated by solar radiation (Brown 1970; LeMone 1973; Cristian and Wakimoto 1989). These vortices have frequently been observed by satellites as cloud streets formed in the updraft regions of the roll circulation. As illustrated in Fig. 1, in their review, Etling and Brown (1993) showed that horizontal scale $\lambda$, vertical scale $H$, and aspect ratio $\lambda/H$ of these horizontal roll vortices range between 2 and 20 km, between 1 and 2 km, and between 2 and 15, respectively. Atlas et al. (1986) observed an ABL over the ocean during cold air outbreaks by utilizing the combination of vertical lidar and in situ meteorological observations from two aircraft, finding updrafts and downdrafts ranging from 2 m s$^{-1}$ to 4 m s$^{-1}$ associated with the horizontal roll vortices. They also documented the existence of waves within the inversion layer above the vortices.

Horizontal flows perpendicular to the roll axes during daytime hours have been observed by Doppler radars through plan position indicator (PPI) scans (Christian and Wakimoto 1989) and range height indicator (RHI) scans (Weckwerth et al. 1996). Weckwerth et al. (1997) showed that a moderate surface sensible heat flux and some vertical wind shear are necessary for sustaining horizontal convective rolls.

Conversely, Wurman and Winslow (1998) reported horizontal roll vortices occurring in different environments from those described above. More specifically, they observed, by Doppler on Wheels, boundary layer rolls in hurricane Fran, which made landfall near midnight. The vertical and horizontal scales of these rolls were 1000 m and 600 m, respectively, while the wind field within 500 m above ground level (AGL) exhibited small-scale spatial variations with alternating bands of intense and weak winds, the former having 40 m s$^{-1}$ to 60 m s$^{-1}$ occurring in downdraft regions, while the latter having 15 m s$^{-1}$ to 35 m s$^{-1}$ in updraft regions.

Here, the horizontal velocity associated with the cross-roll flow (CRF) perpendicular to the large-scale horizontal flow was estimated to be between 3 m s$^{-1}$ and 5 m s$^{-1}$ based on measured Doppler velocities within the regions in which the radar beams were oriented perpendicular to the rolls. Such a structure of horizontal roll vortices suggests that an aircraft encounters alternating strong and relatively weak crosswinds accompanied by tailwinds just after passing a peak of the crosswinds while flying a course perpendicular to the roll axis at low altitudes.

In general, Doppler lidar is effective for observing the organized structure in a dry ABL even when Doppler radar fails to detect clear-air echoes due to
backscattering from refractive-index variations or insects. Drobinski et al. (1998) observed large organized eddies in the ABL by utilizing various instruments including a Doppler lidar focused horizontally along the surface layer. Iwai et al. (2008) observed horizontal convective rolls in the sea-breeze layer below 220 m AGL by using ground-based dual-Doppler lidar. And Shun and Chan (2008) reported Doppler lidar observations of terrain-induced wind shear in dry weather at Hong Kong International Airport.

Finally, we note that LLWS associated with remarkable levels of turbulence has frequently been reported by aircraft landing and taking off at Narita Airport when a strong southwesterly wind prevails, which acts as a crosswind to the runways. In addition to the event noted earlier, another hard landing accident occurred under similar conditions at Narita Airport in 1990, resulting in damage to the fuselage (Japan Transport Safety Board 1992).

The structure of the present paper is as follows. In Section 2, the observational data used for the analysis are described. In Section 3, the topography of Narita Airport and the surrounding area, as well as the synoptic situation are presented. In Section 4, the vertical structure of the ABL and LLWS are examined based on flight data recorder (FDR) data. In Section 5, the spatial structure of the horizontal roll vortices is examined based on Doppler lidar observations. Next, in Section 6, we describe the horizontal roll vortices in terms of how they induce LLWS. Finally, we discuss our findings and provide some conclusions of our study in Section 7.

2. Observations and data used for the analysis

2.1 FDR data

The FDR data from the aircraft that experienced the noted phenomenon were used to analyze the structure of the ABL and LLWS. The aircraft followed a final approach course of 156° magnetic bearing on a glide slope of 3° established in the northwest quadrant of Narita Airport. The aircraft landed on Runway 16R at approximately 0422 UTC (1322 LST) on 20 June 2012 with a ground speed ranging from 74 m s$^{-1}$ to 80 m s$^{-1}$ below 1500 ft (457 m) AGL.

Table 1 shows the FDR data used for our present analysis, including units. Note that 1 ft, 1 knot, and 1 G are equivalent to 0.3048 m, 0.5144 m s$^{-1}$, and 9.807 m s$^{-2}$, respectively. The following subsections detail some of the FDR data and findings.

a. Altitudes

The FDR recorded the height of flight in terms of pressure altitude (PA) and altitude measured by a radio altimeter (RA). More specifically, PA is the height above mean sea level (AMSL) derived from measured outside pressure and the International Standard Atmosphere. Further, RA is the distance between the aircraft and the surface just below the aircraft, the latter being measured precisely by electromagnetic waves radiated from the aircraft. In this section, RA was used for analysis below 100 feet (30 m) above the runway.

b. Wind and LLWS

Wind direction and wind speed are obtained under the assumption that ground speed vector is equal to the airspeed vector plus the wind vector. The magnitude of the wind shear encountered by the aircraft in our present study was determined by variations of the headwind components obtained from both the aircraft’s ground speed and airspeed to which lift force is very sensitive.

c. Aircraft vertical acceleration due to turbulence

The vertical acceleration of an aircraft fluctuates due to not only aircraft maneuvering, but also vertical gusts associated with turbulence consisting of distinctly short period fluctuations as compared to those of the former. More specifically, when an aircraft experiences vertical gust $w'$ associated with turbulence, angle of attack $\alpha$ is changed by an increment of $\Delta \alpha$ as illustrated in Fig. 2, which results in a sudden

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<th>Elements</th>
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<td>feet (ft)</td>
<td>1 foot = 0.3048 m</td>
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<tr>
<td>Wind direction</td>
<td>1 sec</td>
<td>degree (°)</td>
<td>True bearing</td>
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<td>Wind speed</td>
<td>1 sec</td>
<td>knot (kt)</td>
<td>1 knot = 0.5144 m s$^{-1}$</td>
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<td>Outside air temperature</td>
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<td>Air speed</td>
<td>1 sec</td>
<td>knot (kt)</td>
<td>CAS (Computed Air Speed)</td>
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<tr>
<td>Ground speed</td>
<td>1 sec</td>
<td>knot (kt)</td>
<td>GS (Ground Speed)</td>
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<tr>
<td>Vertical acceleration</td>
<td>0.125 sec</td>
<td>G</td>
<td>1 G = 9.807 m s$^{-2}$</td>
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The increment of lift coefficient $\Delta C_L$. This increment causes a fluctuation of lift $L$, after which the aircraft responds to the fluctuation with vertical acceleration $AV$ within a short time period.

In reality, this acceleration is slightly alleviated depending on the characteristics of the airframe, but the qualitative analysis of the effects of turbulence do not change. Here, $L$, $\Delta C_L$, and $AV$ are written as follows:

\[ L = \frac{1}{2} C_L \rho V^2 S, \quad (1) \]
\[ \Delta C_L = \frac{\partial C_L}{\partial \alpha} \Delta \alpha, \quad (2) \]
\[ AV = g \left( 1 + \frac{\Delta C_L}{C_L} \right). \quad (3) \]

Here, $C_L$ is the lift coefficient before experiencing the vertical gust, $V$ is airspeed, $\rho$ is air density, $S$ is the wing area, $\Delta \alpha (rad) = \frac{w^\prime}{V}$, and $g$ is the acceleration of gravity.

### 2.2 Doppler lidar

A Doppler lidar (hereafter simply referred to as lidar), which is able to detect backscattering from aerosols, was installed and operated to surveil LLWS and turbulence in clear-air at Narita Airport (Yamamoto 2009). This lidar operates at a wavelength of 2.0 $\mu$m, with a range resolution of 100 m and a maximum range of up to 10 km. Further, this lidar operates automatically 24 hours a day according to a prescribed scan strategy that includes PPI scans at elevation angles of 1° and 3°, lidar RHI scan beams with an azimuth of 336° magnetic bearing, and a glide slope of 3°. The height of the transmitter and receiver of the lidar sat at 13.9 m above the threshold of runway 16R. This lidar was the only observational equipment available to capture the organized structure in the ABL.

During the event we focused on in our study, some scattered clear-air echoes were detected by the Doppler Radar for Airport Weather at Narita Airport, but these echoes were too sparse to be used for analyzing the present meteorological event. Further, since there were almost no clouds or precipitation during this time period, the lidar was the only observational equipment available to capture the organized structure in the ABL.

Figures 3 and 4 show the location of the lidar and the spatial relations among the final approach course on runway 16R, the threshold of runway 16R, lidar PPI scan beams with elevation angles of 1° and 3°, lidar RHI scan beams with an azimuth of 336° magnetic bearing, and a glide slope of 3°. The height of the lidar was directed toward magnetic north, and the magnetic variation at Narita Airport was 7°W when this event occurred. Finally, the landing aircraft approached with a glide slope of 3° and landed on the runway after passing the runway threshold at 50 ft (15 m) AGL.

### 2.3 Surface wind

There were four anemometers set up to measure instantaneous wind every three seconds; these obtained two-minute average and ten-minute average wind near the end of runways 16R/34L and 16L/34R. (Note
that the specific locations of runways 16R/34L and 16L/34R are shown in Figs. 15, 17.) As shown in Fig. 3, the height of the anemometer of runway 16R, which was located near the touch down point of the aircraft, was 9.6 m. And the wind data measured by the anemometer of runway 16R were primarily used for our present analysis.

3. Environment

3.1 Topography

Narita Airport is located at approximately 40 m AMSL on the Shimofusa tableland in the Kanto Plain. As illustrated in Figs. 5 and 6, this airport is adjacent to the lowlands of the Tone River to the north, Lake Inba to the west, the Kujyukuri coast to the southeast, and a broad expanse of land to the southwest of windward that faces Tokyo Bay.

The Shimofusa tableland is macroscopically fairly flat but microscopically rugged due to many shallow valleys running in all directions. Within this region, the elevation differences between the top of the tableland and the bottom of the valleys is about 30 m.

3.2 Synoptic situation

Turning to synoptic situation, as shown in Fig. 7 an extratropical cyclone of 998 hPa transitioned from a tropical cyclone located in the Pacific Ocean east of the Tohoku District, while another extratropical cyclone of 996 hPa in the Sea of Japan was moving east at 06 UTC (15 LST) on 20 June 2012. Though a cold front extending southwestward from the center of the former cyclone is shown in Fig. 7, it was not distinct around the Kanto District because no discontinuities in temperature and wind fields appeared there. As indicated in Fig. 8 the latter cyclone strengthened the southwesterly flow in the southern Kanto Plain between the surface and 850 hPa. Note that the presence
of a cyclone in the Sea of Japan is a typical situation in which strong southwesterly winds prevail across the southern Kanto Plain.

3.3 Local meteorological conditions

Figure 9 shows wind and temperature distributions observed by the Automated Meteorological Data Acquisition System (AMeDAS) stations within the area, including at Narita Airport at 04 UTC (13 LST) on 20 June 2012. From these data, southwesterly winds prevailed across the southern Kanto Plain and a region of wind speed exceeding 7 m s$^{-1}$ were distributed over the Shimofusa tableland, including Narita Airport. A shear line running from southeast to northwest across the coastline was located approximately 50 km north of Narita Airport; however, there was no discontinuity in the wind field within 50 km of the airport.

The hourly duration of sunshine measures that contribute to unstable stratification were also observed at AMeDAS stations around Narita Airport. These data showed 0.7 to 1.0 hours of sunshine between 01 and 03 UTC (10 and 12 LST) and 0.0 to 0.4 hours of sunshine between 04 and 05 UTC (13 and 14 LST) on the date of the event. Further, as summarized in Table 2, the duration of sunshine and global solar radiation observed at Tateno at 05 UTC (14 LST) were recorded as 0.6 hours and 2.49 MJ m$^{-2}$, respectively.

3.4 Geostationary satellite images and vertical sounding

Figure 10 shows the visible imagery of MTSAT-2 at 0430 UTC (1330 LST), which reveals a cloud area
with longitudinal and latitudinal dimensions of approximately 50 km around Narita Airport.

According to upper-air observations at Tateno at 00 UTC (09 LST), as shown in Fig. 11, the convective mixed layer developed from the surface (995 hPa) to 907 hPa with a nearly adiabatic lapse rate. This convective mixed layer was capped by an inversion layer with a local maximum wind speed of 28 knots (14.4 m s\(^{-1}\)) at 919 hPa around the bottom of the inversion layer. The convective mixed layer was dry with a dew point depression ranging from 4.8°C to 10.0°C. Further, the lifting condensation level was 855 hPa and no level of free convection existed. The moist layer was observed only at approximately 500 hPa.

Routine aeronautical meteorological observation at Narita Airport at 0400 UTC (1300 LST) reported stratocumulus with a cloud amount of 1/8 and cloud bases of 2500 ft (762 m) AGL in the ABL, as well as altocumulus with a cloud amount of 5/8 and cloud bases of 18000 ft (5486 m) AGL at approximately 500 hPa. Therefore, we consider the cloud area observed by the satellite around Narita Airport to correspond with the moist layer between 500 hPa and 437 hPa from these upper-air observations. Further, these observations show that no cloud streets appeared in the ABL.

### 3.5 Surface wind

Figure 12 shows the wind direction, wind speed, gust factor, and wind component along the runway direction, as observed at runway 16R for one hour around the landing time of the aircraft. The surface wind direction and speed at 0422 UTC (1322 LST) when the aircraft landed was 235° magnetic bearing.
and 11 knots (5.7 m s\(^{-1}\)), respectively, with gusts as high as 23 knots (11.8 m s\(^{-1}\)) and a gust factor of 2.09. Gust factors during this hour ranged between 1.67 and 2.67, thereby indicating the persistence of a remarkably turbulent flow. Further, a tailwind component of 5 knots (2.6 m s\(^{-1}\)) and higher appeared intermittently.

According to statistics covering a seven-year period at Narita Airport (Narita Aviation Weather Service Center 2004) between 1996 and 2002, the gust factor when the wind direction was from the southwest quadrant typically ranged from 1.67 to 1.71, while the gust factor covering a 10-year period at Chubu International Airport near Nagoya surrounded by the sea is 1.17 to 1.30 (Chubu Aviation Weather Service Center 2016) between 2005 and 2015. Therefore, we observe here that Narita Airport generally faces stronger turbulence when southwesterly wind prevails.

4. FDR data analysis

4.1 Temperature and potential temperature

Figures 13a and 13d show the vertical distributions of both static air temperature and potential temperature, respectively, as obtained from the FDR data. The convective mixed layer (ML), entrainment zone (EZ), and free atmosphere (FA) analyzed from their distributions are also indicated. Here the EZ is characterized by a temperature inversion with its top being approximately 938 m AGL. Further, the fluctuations in potential temperature within the ML was much greater than those of the FA, as shown in Fig. 13d. In particular, fluctuations reached 1.2 K near the surface, suggesting the presence of strong vertical mixing close to the surface.
Fig. 13. Vertical profiles of (a) outside air temperature, (b) wind direction, (c) wind speed, (d) potential temperature, and (e) vertical acceleration measured by the aircraft landing at Narita Airport at approximately 0422 UTC (1322 LST) on 20 June 2012. Here, (a) shows static air temperature and (b) shows the true bearing. The vertical axis is the recorded pressure altitude, with its value at the touchdown point on the runway 16R (i.e., 130 feet AMSL) at 545 feet. Labels FA, EZ, ML, and GL denote the free atmosphere, entrainment zone, convective mixed layer, and ground level, respectively.
4.2 Winds

During the present event, a low-level jet with a maximum wind speed of 52 knots (26.8 m s\(^{-1}\)) was present between 462 m and 642 m AGL, corresponding to the upper ML and EZ. And as shown in Fig. 13c, this was accompanied by a significant vertical wind shear that reached 16.5 knots/1000 ft (i.e., 2.78 \(\times 10^{-2}\) s\(^{-1}\)) through the ML. A similar wind speed maximum was also present in the upper-air observations at Tateno, as illustrated in Fig. 11. Here, the development of horizontal roll vortices in the ML given vertical wind shear conditions is indeed consistent with previous theoretical studies on thermal convection (e.g., Asai 1970).

Finally, the mean wind direction in the ABL was 230° (or 237° magnetic bearing), while the mean wind direction in the FA was 250° (or 257° magnetic bearing), revealing a veering of approximately 20° near the top of the ABL.

4.3 Aircraft vertical acceleration

The vertical acceleration is recorded eight times per second by the FDR of the aircraft as it penetrates through the ABL, thus providing direct meteorological data that indicates turbulence. Figure 13e shows the vertical distribution of the aircraft vertical accelerations, with maximum values at each second shown in the plot. Although the fluctuations of the aircraft vertical acceleration were small in the FA and EZ, they grew very large in the ML, reaching \(\pm 0.3\) G near the surface.

4.4 LLWS

In our present analysis, as introduced in Section 2.1b above, the magnitude of the LLWS encountered by the aircraft is defined as the variation of headwind components obtained by the following relation:

\[
\text{Headwind component} = \text{Airspeed (CAS)} - \text{Ground speed (GS)}.
\]

Here, if CAS is greater than GS, the aircraft experiences a headwind; and conversely, if CAS is less than GS, the aircraft experiences a tailwind.

Figure 14 shows the CAS and GS at each second during the landing. We observe here that LLWS was characterized by a change from a headwind component of 5 knots (2.6 m s\(^{-1}\)) upon passing the runway threshold to a tailwind component of 10 knots (5.1 m s\(^{-1}\)) just before touchdown, all of which occurred in five seconds. The distance between the runway threshold and the touchdown point was approximately 400 m. Therefore, the magnitude of the horizontal wind shear was 15 knots/400 m (i.e., \(1.9 \times 10^{-2}\) s\(^{-1}\)).

According to the routine and special aeronautical meteorological observation reports for Narita Airport on 20 June 2012, numerous aircraft landing on and taking off from runways 16R and 16L between 0605 LST and 1757 LST reported frequent encounters with LLWS and moderate turbulence. Changes in the airspeed of these aircraft due to LLWS typically ranged from \(\pm 10\) knots (5.1 m s\(^{-1}\)) to \(\pm 20\) knots (10.3 m s\(^{-1}\)) at 300 feet (91 m) AGL or lower. Further, five landing aircraft, including two aircraft approaching runway 16L, made go-around due to wind shear between 1000 LST and 1500 LST on 20 June 2012 (Japan Transport Safety Board 2016).

5. Doppler lidar observations and analysis

5.1 Doppler velocity

a. PPI scans

Figure 15 shows the lowest 1°-elevation PPI scan of Doppler velocity at 04:22:20 UTC (13:22:20 LST) on 20 June 2012 when the aircraft encountered LLWS and landed at Narita Airport. The southwest quadrant of the 1°-elevation PPI scan was undetectable due to obstacles. Therefore, to properly analyze wind speed, we examined the sector between magnetic bearing 22°
and 82°, which is nearly parallel to the wind direction from magnetic bearing 232°, at which the Doppler velocity was between 86.6 % (cos 30°) and 100 % (cos 0°) of the actual wind speed.

Through our analysis, we observed that the PPI scan of the Doppler velocity clearly shows the existence of alternating high- and low-speed wind bands that were oriented nearly parallel to the mean flow. The thin blue solid line oriented at 142°–322° in the magnetic direction is perpendicular to the mean flow and crosses the lidar site. The numbered red circles on the thin blue solid line indicate FTL. The black and gray dashed lines indicate the final approach course (APP CRS) for runway 16R and the lidar RHI azimuth of 336° magnetic bearing, respectively. Runways 16R and 16L are indicated as RWY16R/34L and RWY16L/34R, respectively. The arrows labeled TN and MN in the lower-left corner indicate the directions of true north and magnetic north, respectively.

Within these two kinds of bands was therefore approximately 2.0, which is rather similar to the boundary layer rolls observed in hurricane (Wurman and Winslow 1998), though their formation mechanisms seem to differ. The height of the lidar beams at the crossing points between lines A, B, and C and the centerlines of the high-speed wind bands ranged from 56 m to 105 m AGL, i.e., the lower portion of the ML.

Finally, we observed that three of these high-speed wind bands appeared on runway 16L/34R, which has a length of 2500 m and is located approximately 3.5 km north-northeast of runway 16R/34L.

Turning our attention to flow perpendicular to the mean flow, as illustrated in Fig. 15, we note that the Doppler velocity along magnetic bearing 322°, which is perpendicular to the mean flow, indicates alternating patterns of flow toward lidar (FTL) and flow away from lidar (FAL). Christian and Wakimoto (1989) also observed similar patterns caused by the counterclockwise rotation of horizontal convective rolls by a Doppler radar.

Note that the red numbered circles in Fig. 15 indicate that the FTL existed at a horizontal spacing that ranged from 700 m to 900 m within a range of 5 km. Doppler velocities of FTL and FAL were between $-1.0 \text{ m s}^{-1}$ and $-5.0 \text{ m s}^{-1}$ and between $+1.0 \text{ m s}^{-1}$ and $+5.0 \text{ m s}^{-1}$, respectively, at a beam height ranging from 18 m to 94 m AGL.

b. RHI scans

Figure 16 shows an RHI scan of the Doppler velocity at an azimuth of 336° magnetic bearing which is parallel to the final approach course of the aircraft and runway 16R at 04:22:54 UTC (13:22:54 LST) on 20 June 2012. This azimuth from the RHI scan lies 14° east of magnetic bearing 322°, which is perpendicular to the mean flow. Further, Fig. 16 shows that the FAL below 900 m AGL and the FTL above 900 m AGL correspond to wind directions of 237° in the ABL and 257° in the FA, respectively, which were measured by the aircraft itself.

Here, the former was directed slightly more toward the lower pressure side by approximately 20°. Therefore, we conclude that a height of 900 m AGL seems to be rather consistent with the height of the top of the ABL obtained from FDR data. Undulations within the near-zero Doppler velocity zones existed in the upper ABL, suggesting existence of atmospheric waves, as previously shown by Atlas et al. (1986).

5.2 DSW

When the ABL is moist, organized structures such
as horizontal roll vortices can be visualized as cloud streets that form within updraft; however, no cloud formation was observed in our present case since the ABL was primarily dry. We therefore attempt to obtain additional information regarding the vertical flow from the aforementioned DSW, which provides a good measure of turbulence intensity. According to the vertical acceleration of the aircraft recorded by the FDR, as illustrated in Fig. 13e, turbulence intensity was at its minimum within the upper ML, then it increased and reached its maximum near the surface.

When horizontal roll vortices are present, downdrafts (updrafts) in their circulation would transport less (more) turbulent air downward (upward). Although turbulence energy can be generated locally and advected horizontally, the vertical advection described above would tend to produce bands of DSW minima and maxima that are aligned in the mean wind direction and alternate within the cross-stream direction. If such a DSW pattern is formed instead of cloud streets, it would provide useful observational information that we can utilize to infer vertical flows.

In our present study, we examined observation data detected by 3°-elevation PPI scanning near the mid-level of the ML because the specific DSW pattern described above is indistinct within the lower ML in which surface-generated turbulence is dominant.

a. PPI scans

As detailed in Fig. 17, a 3°-elevation PPI scan of DSW at 04:21:11 UTC (13:21:11 LST) on 20 June 2012 (Fig. 17) shows bands of DSW minima and maxima with axes parallel to the mean flow. These bands alternated perpendicular to the mean flow. Note that the height of the 3°-elevation angle at a range of 5...
km is 276 m AGL, which corresponds to the mid-level of the ML. These DSW minimum bands were particularly distinct, the spacing between adjacent bands along line A being approximately 800 m.

Further, the DSW minimum bands did not always exhibit a homogeneous band-like structure, instead consisting of several blocks of small DSW bands that were aligned nearly in a straight line, possibly reflecting inhomogeneity of the vertical flows or other factors. In our present study, this straight line is denoted as the centerline of the DSW minimum band.

The DSW minimum bands are indicated by circles along line A of Fig. 17 and correspond to the high-speed wind bands shown in Fig. 15 in which line A and the numbered black circles in this figure are co-located with those of Fig. 17. Further, one DSW minimum block and two DSW minimum bands located on runway 16L/34R distinctly corresponded to the high-speed wind bands in Fig. 15. The fact that the DSW minimum bands are co-located with the high-speed wind bands suggests that these bands are associated with downdrafts that transport the large momentum of the low-level jet and the air with weak turbulence in the upper ML.

Also from Fig. 17, large DSWs were found within the white thick-dashed circle. The beam height at this circle is approximately 50 m AGL. We may interpret this finding as indicating that strong turbulence exists near the surface everywhere and is not confined to the vicinity of the lidar site.

The white thin circles in Fig. 17 indicate the FTLs along the line perpendicular to the mean flow in Fig. 15. These FTLs were on the lidar side of the centerlines of the DSW minimum, suggesting that the DSWs were smaller along the lines where downdrafts associated with the horizontal roll vortices were expected. This feature occurred consistently except for FTLs numbered 1 and 2 in which turbulent air flow prevailed near the surface.

### b. RHI scans

Figure 18 shows the RHI scan of DSW at 04:22:54 UTC (13:22:54 LST) on 20 June 2012 at azimuth of 336° magnetic bearing, which is parallel to the final approach course and runway 16R. The numbered white arrows indicate the DSW minima that appeared periodically at a spacing of 600 m to 900 m within the middle and lower parts of the ML. We conclude here that the less turbulent air parcels in the upper ML sank in the downdraft regions of the roll circulations. In particular, DSW minimum 1, which had nearly the same DSW value as the FA was found to intrude below 200 m AGL right above the threshold of runway 16R.

Further, the numbered red belts attached at the bottom of the figure identify the FTL locations, which are estimated by shifting the red circles in Fig. 15 to the RHI azimuth of 336° along the centerlines of the DSW minimum bands. We observe here that the FTLs located slightly on the lidar side of or nearly co-located with the DSW minima in the ML.

Next, Fig. 19 shows a similar plot as that presented...
Three remarkable DSW maxima extending from the surface to nearly the top of the ML with a spacing of 900 m to 1000 m existed between 4 km and 7 km. These maxima were detected at nearly the same positions as the relatively large DSWs shown in Fig. 18, suggesting that the strong turbulence generated near the surface was transported upward in updraft regions of the roll circulations and the positions of these roll circulations were almost stationary for at least two minutes and 27 seconds.

Figure 19 also shows the small DSWs distributed from the top of the ML to approximately 250 m AGL, as well as the large DSWs near the surface between 1.3 km and runway threshold. Finally, Fig. 20 shows a 1°-elevation PPI scan 33 seconds prior to what is presented in Fig. 19; comparing these two figures, we were able to detect large DSWs co-located with the high-speed wind band close to the runway threshold. Further, these figures suggest
that the strong turbulence in the thin layer near the surface was generated by high-speed winds caused by the downdraft transporting the high momentum in the upper ML downward.

6. LLWS induced by horizontal roll vortices

a. Structure of the horizontal roll vortices

In Fig. 21 and Table 3, we present the schematic and specific characteristics, respectively, of the horizontal roll vortices observed at Narita Airport on 20 June 2012. The ML had a nearly dry adiabatic lapse rate that developed beneath the inversion layer. The thickness of the ML was approximately 500 m, while the top of the ABL was approximately 900 m AGL.

The horizontal roll vortices have their axes in the direction of the mean flow; further, they have alternating rotational directions that appear to be caused by daytime surface heating under significant vertical wind shear, i.e., approximately $3 \times 10^{-2}$ s$^{-1}$, within the ML, which is greater than that reported by Weckwerth et al. (1997), i.e., approximately $2 \times 10^{-3}$ s$^{-1}$.

Here, horizontal scale $\lambda$ of a pair of counter-rotating vortex rolls, which is also the distance between adjacent high-speed wind bands, was approximately 800 m. The high-speed (low-speed) wind bands parallel to the rolls that should be caused by downdrafts (updrafts) transporting high (low) momentum downward (upward) from the upper ML (near the surface) alternated along the direction perpendicular to the mean flow. The CRFs, which are the flows perpendicular to the roll axis with an amplitude of approximately 5 m s$^{-1}$ in the lower ML (as shown earlier in Fig. 15), formed the LLWS along a narrow distance within $\lambda$.

PPI scans of the Doppler lidar further show that the high-speed wind bands are co-located with the DSW minimum bands, while the relatively low-speed wind bands are co-located with the DSW maximum bands. We propose here that this occurs possibly because more turbulent air generated near the surface was transported upward by the updrafts in roll circulations, while less turbulent air in the upper ML was transported downward by downdrafts.

When a landing aircraft flies at a GS of 155 knots (80 m s$^{-1}$) through the ML in which the mean flow is perpendicular to the final approach course, the aircraft repeatedly experiences a 10-second cycle of the following four stages: (1) an updraft with relatively weak crosswinds and strong turbulence; (2) a headwind of CRF; (3) a downdraft with strong crosswinds and relatively weak turbulence; and (4) a tailwind of CRF. In addition to this LLWS, the aircraft continuously experiences strong turbulence near the surface that is more intense than that of the lowest part of the downdraft regions as described in Section 5.2 above. Further, the distribution of turbulence intensity within the thin layer near the surface differs from what presents in the ML.

Finally, we note wavy undulations existed in the EZ, characterized by an inversion. Using an airborne lidar, Atlas et al. (1986) reported 1 km to 2 km scale

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**Table 3.** Characteristics of the atmospheric boundary layer and the horizontal roll vortices shown in Fig. 21.

<table>
<thead>
<tr>
<th>$\lambda$ (m)</th>
<th>$Z_i$ (m)</th>
<th>$\lambda/Z_i$</th>
<th>$Z_j/Z_i$</th>
<th>$h$ (m)</th>
<th>$CRF$ (m s$^{-1}$)</th>
<th>$V_H$ (m s$^{-1}$)</th>
<th>$V_L$ (m s$^{-1}$)</th>
<th>$V_H/V_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>500</td>
<td>1.6</td>
<td>0.9–1.3</td>
<td>900</td>
<td>5</td>
<td>15–20</td>
<td>5–10</td>
<td>2.0</td>
</tr>
</tbody>
</table>
roll vortices and corresponding undulations of the inversion with an amplitude of 150 m to 200 m at the boundary between FA and ABL together with entrainments across the EZ.

b. _LLWS induced by the horizontal roll vortices_

To properly analyze the structure of the LLWS induced by horizontal roll vortices in more detail, the region adjacent to the runway threshold shown in Figs. 15, 17, and 18 are enlarged in Figs. 22b, c and a, respectively. A high-speed wind band with a width of approximately 200 m (Fig. 22b) and the DSW minimum region with a dimension of approximately 360 m × 710 m (Fig. 22c) appeared at the same location adjacent to the runway threshold. Figure 22a indicates that the space of the small DSWs in RHI scans appeared just above the runway threshold, suggesting that air parcels in the upper ML were transported downward to approximately 150 m AGL or below. Further, the DSW minimum close to the runway threshold shown in Fig. 22c was detected at approximately 40 m AGL, thereby suggesting that the downdraft extended to near the surface.

Figure 23 shows the lowest 1°-elevation PPI scan of DSW at 04:22:20 UTC (13:22:20 JST). The large DSWs that indicate intense turbulence were detected on the high-speed wind band across the runway threshold (Fig. 22b). The height of the lidar beams

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**Fig. 22.** Enlarged view of (a) the RHI scan of the DSW, (b) the PPI scan of the Doppler velocity, and (c) the PPI scan of the DSW near the threshold of runway 16R in Figs. 18, 15, and 17, respectively. The color scales are the same as in the original figures.

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**Fig. 23.** The 1°-elevation PPI scan of DSW at 04:22:20 UTC (13:22:20 LST) on 20 June 2012. Here, large DSWs were detected within the region shown, which has a width of approximately 300 m across the runway threshold, as indicated by solid lines and arrows. As shown in the figure, the height of the lidar beams crossing these large DSWs on the final approach were below 30 m AGL. The thin black dotted lines, thin black dashed lines, and thin gray dashed lines are the same as shown in Fig. 20.
crossing these large DSWs on the final approach course are consistently below 30 m AGL.

Figure 24 shows a comprehensive schematic of the LLWS induced by the horizontal roll vortices, as revealed from Figs. 14, 21, 22, and 23 above. More specifically, the landing aircraft experienced a tailwind immediately after passing the downdraft region with high-speed crosswinds and intense turbulence, where the width of the downdraft region was approximately 200 m. The distance between the runway threshold and the touchdown point was approximately 400 m, or approximately half of the horizontal scale $\lambda$ of the horizontal roll vortices. Further, the velocity of the tailwind almost corresponded with the CRF velocity observed by the lidar.

In addition to LLWS, the aircraft should experience a change in airspeed due to the intense turbulence near the surface during landing. When a high-speed wind band is located at the runway threshold, a landing aircraft would simultaneously encounter a strong crosswind and intense turbulence followed by a tailwind with a relatively weak crosswind just before touchdown.

Figures 20, 22b and 23 provide further observational information that indicates that the high-speed wind band associated with large DWSs shifted approximately 400 m from the runway threshold to the north over two minutes and 28 seconds. This suggests a temporal variation of the LLWS due to roll drift, as previously described by Drobinski et al. (1998).

Another hard landing event occurred at Narita Airport at approximately 0512 UTC (1412 LST) on 24 March 1990 (Japan Transport Safety Board 1992). The landing aircraft experienced a sudden weakening of the southwesterly crosswind of 40 knots (20.6 m s$^{-1}$) and a significant wind direction change at 15 m AGL followed by a temporary tailwind at 12 m AGL. During the landing, the airspeed of the aircraft decreased 12 knots (6.2 m s$^{-1}$) in only one second. This tailwind experienced immediately after passing the crosswind peak is strikingly similar to that of the structure shown in Fig. 24.

7. Discussion and conclusions

From our present study, we revealed the existence and structure of horizontal roll vortices by analyzing lidar observations and FDR data of an aircraft that experienced a hard landing at Narita Airport in Japan. More specifically, these observations captured the unique features of horizontal roll vortices, which are the high-speed wind bands, the CRFs, DSW minimum bands in PPI scans, and DSW distributions that sug-
suggested vertical flows in RHI scans. In particular, using CRFs as horizontal components and DSW minimum bands as vertical components of vortices, we successfully identified the existence of roll circulations with horizontal axes.

We proposed that DSW minimum bands co-located with high-speed wind bands could be used as indicators of downdrafts of horizontal roll vortices similar to how cloud streets can indicate updrafts of roll circulations; here, downdrafts transport less turbulent air downward with a large momentum of the low-level jet from the upper ML. Note that this relation between downdrafts and high-speed wind bands is similar to that of horizontal rolls in a hurricane boundary layer (Wurman and Winslow 1998), though the cause of the rolls seems to be different. It seems that the large gust factors of surface winds, such as those at 2.0 or greater, were caused not only by the roughness of the topography, but also by the downward transport of momentum of the low-level jet due to the downdrafts of roll circulations.

Further, the horizontal and vertical scales of the horizontal roll vortices were smaller than the majority of previous studies, except for Wurman and Winslow (1998) in which they are 1000m or less. The horizontal scale of approximately 800 m in our present case caused LLWS to form within a narrow space between the runway threshold and the touch-down point.

In the downdraft region of the roll circulation, the turbulence is intensely generated within the thin layer near the surface, though the less turbulent air space is distributed in a deep layer right above the thin layer in the ML.

We also revealed that the LLWS encountered by the aircraft was caused by CRFs associated with organized horizontal roll vortices, as analyzed. Here, LLWS caused a change in airspeed to 15 knots (7.7 m s\(^{-1}\)), which was less than those caused by microbursts, gust fronts, and the like. As an example, wind shear due to a microburst can exceed 50 knots (25.7 m s\(^{-1}\)) (Fujita 1985); however, horizontal roll vortices occur in an ABL over a wide area with small spacing and can last anywhere from several hours to half a day depending on the synoptic situation; therefore, the probability that a landing aircraft encounters LLWS is much higher than encountering a microburst, a gust front, a cold front, or similar such event.

When the wind direction is perpendicular to the runway at Narita Airport, rolls with axes aligned with the mean wind develop. A landing aircraft below 15 m AGL then experiences flow changes from a headwind component to a tailwind component in a short span of approximately 400 m. Consequently, as the landing aircraft decreases airspeed to land, the aircraft experiences further loss of airspeed right before touchdown. This kind of LLWS might certainly occur at other airports given strong crosswinds to their runways during daytime hour on a clear day; however, examining whether LLWS causes hard landings at these airports is not easy to accomplish by same approach because the Doppler lidars for routine observations have only been installed at three major airports in Japan, one of which being Narita Airport. We therefore expect that a numerical simulation could be an effective method to further examining LLWS.

While the present study examined an LLWS event associated with horizontal roll vortices and strong turbulence in strong southwesterly winds and daytime unstable stratification, similar structures in the ABL have been found by lidar observations and FDR data at Narita Airport, even when wind directions differed (Yoshino et al. 2013): For example, in northwesterly winds under a winter pressure pattern or northeasterly winds caused by a cyclone propagating along the southern coast of the Japanese island. A further study on roll vortices in various environments is desired to clarify whether horizontal roll vortices and the topography of the Shimofusa tableland with its shallow valleys are responsible for the LLWS, remarkable turbulence, and large gust factors.

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