Analysis and numerical simulation of a waterspout at the Hong Kong International Airport

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Abstract

The wind field of a waterspout that occurred near the Hong Kong International Airport was documented using dual-Doppler analysis from a dense network of Doppler Light Detection and Ranging (LIDAR) systems operated at the airport, and nearby surface weather station observations. The dual-Doppler winds are used in tandem with surface observations to analyze the wind structure of the waterspout. The performance of a numerical weather prediction system simulating the windshift line and the associated vortices is compared to the observations. The waterspout and the other vortices formed along a windshift line (convergence between the arriving northeast monsoon and background westerly/sea breeze) and were rather weak, with the surface wind gusting to about 10 m/s. However, the dense network of meteorological sensors at the airport provided unprecedented surface sampling of these vortices. The numerical model captured the convergence line and the vortices reasonably well and may provide earlier alerting to the aviation weather forecasters about the possible occurrence of small waterspout-type vortices near the airport, which may have implications to aviation safety.

Keywords: waterspout, NWP, LIDAR

1 Introduction

Waterspouts have been observed infrequently in Hong Kong, about 0.64 per year, on average. According to Chen et al. (2018), there are about 20–30 tornados over southern China in a study period of 64 years (1948 to 2012) and thus waterspouts/tornados are not quite common in south China coastal areas. From Yao et al. (2015), tornados are mostly observed over southern China in the summer, namely, in the period of June to September. There is also a decreasing trend of tornado occurrence in the region in the study period of 1960 to 2009.

In the early days, tornados/waterspouts were mostly observed and analyzed using Doppler radar data. Some notable examples are found in Wakimoto and Lew (1993) and Brady and Szoke (1989). In particular, the latter analyzed a non-mesocyclone tornado similar to a waterspout. Some recent studies of waterspouts/tornados could be found in Van den Broeke et al. (2015) and Sugawara and Kobayashi (2008). The former is novel in the analysis of the waterspout using dual-polarization Doppler radar data. A review of the current knowledge of waterspout could be found in Miglietta (2019). A climatological study of waterspouts in Germany, with detailed analysis of some notable examples, could be found in Dotzek et al. (2010).

In particular, some analysis using sounding data has been presented.

Detailed meteorological measurements of the waterspouts are rare. As a result, when they occur within the coverage of meteorological sensors, detailed analyses of the data can provide insight on the characteristics, structure, and evolution of the vortices associated with the waterspouts. There are some reports of waterspouts/tornadoes sighted at Hong Kong International Airport (HKIA), e.g., Hon et al. (2021). Though the waterspouts in Hong Kong are generally weak, they still can still produce winds that could impact the airport and other operations, so understanding their behavior and structure is useful in many applications, e.g., wind engineering for buildings. Waterspouts that occur near the airport have aircraft safety implications, and analysis using the relatively dense meteorological data offers the potential to inform the analysis of such systems in southern China, in which observational data for waterspouts/tornadoes are still relatively rare.

On the afternoon of 25 September 2020 (local time), a waterspout was observed, photographed, and videoed while crossing parts of HKIA in areas of water being reclaimed to land on the north side (Fig. 1). Though weak, the waterspout was visually observed for approximately 20 minutes (starting about 16:00 local time, 08:00 UTC), and passed among the relatively dense network of weather stations and buoys on and around the airport. Other weaker vortices were present as well. At HKIA, there is a suite of meteorological sensors, in-
including Doppler Light Detection and Ranging (LIDAR) systems and surface station observations, that monitor the weather conditions near the airport continuously. In particular, a short-range LIDAR (SRL) and two longer range LIDARs (LRL) were collecting data at the time of the waterspout occurrence, allowing an analysis of the winds within and around the waterspout and other vortices, and comparisons with the weather station wind data. These observations enable a unique and detailed analysis of the structure of the vortices.

According to the knowledge of the authors, waterspout analysis using LIDAR data is rather rare. The present paper is novel in the presentation of the analysis of the structure of a waterspout and the vortices nearby using Doppler LIDAR observations.

Moreover, the capability of a numerical weather prediction model (namely, Weather Research and Forecasting model, or WRF in short) in simulating the vortex will be examined. While the model may not fully reproduce all observed features, it is still found to be able to provide some hints about the occurrence of the smaller vortices in the airport area.

The structure of the paper is as follows. Section 2 is an overview of the synoptic background of the event. The meteorological data considered in this analysis are introduced in Section 3. Their analysis methods are briefly described in Section 4. The analysis results, including the results of numerical weather prediction model are presented in Section 5. The conclusions of the study are drawn in Section 5.8.

2 Synoptic background

At 14:00 local time (06:00 UTC) a weak surge of northeast monsoon was reaching Hong Kong (Fig. 2a). Surface isobars show that the monsoon was weak. Data from the 00:00 UTC upsonde launch was the nearest in time to the event. The corresponding tephigram is shown in Fig. 2b. The K-index is 29 degrees and convective available potential energy (CAPE) could not be determined due to the occurrence of mid-level temperature inversion associated with the northeast monsoon. In general, from the ascent data, the atmosphere was not very convectively unstable.

Fig. 3 shows the time series of the surface weather observations at the airport upon the arrival of the easterlies (associated with the northeast monsoon). At the location of the easterlies, there were also 20 dBZ echoes visible in microwave weather radar data. The easterlies converged with the background westerlies on the eastern side of the airport. The westerlies may have been related to the occurrence of sea breeze. The wind convergence line gradually moved from east to west. At this convergence line a number of vortices appeared from the Doppler LIDAR observations, and are analyzed in detail in Section 5 of this paper.

3 Meteorological data

3.1 Long-range LIDAR (LRL)

The LRLs, HKG1 and HKG2 (locations in Fig. 4), provided data to a maximum range of 20.0 km with azimuthal data spacing of 0.8 degrees and radial gate spacing of 100 m at constant elevation angles of 3 and 6 degrees. The LRLs operate with a wavelength of about 1.6 microns and are used to detect low level windshear and turbulence associated with terrain near HKIA. Some information about the application of LRLs at HKIA could be found in Shun and Chan (2008). Interspersed between the specialised scans for operational alerting of windshear, planar scans (plan position indicator, PPI) at the above two elevation angles were available about every 45 seconds. While LIDARs are effective mainly during clear air (or precipitation-free) conditions, for this case, the precipitation radar echoes around HKIA were sufficiently weak to allow effective coverage over the area of interest.

3.2 Short-range LIDAR (SRL)

The SRL (location in Fig. 4) provided data to a maximum range of 3.0 km with azimuthal data spacing of 2 degrees and radial gate spacing of 30 m at an elevation angle of 5 degrees. Data sweeps were available approximately every minute. It operates at a wavelength of about 1.6 microns. This equipment is mainly used to detect airflow disturbances associated with buildings and enable alerts (see Hon et al., 2014; Hon and Chan, 2020 for detailed discussion).

3.3 Surface automatic weather stations

The location of select weather stations are shown in Fig. 4. They reported 1 Hz wind speed (m/s) and direction at 10 metres above ground level (AGL). They are mostly located along regularly spaced sites along the airport runways and also on some of the islands around HKIA. The weather buoy data (WB stations) are not included in this analysis as they are quite far away from the vortices.
Figure 2: Surface isobaric chart at 06 UTC and tephigram at 00:00 UTC, 25 September 2020.

Figure 3: Surface weather observations, location of the windshift line (red) and weather radar echoes in the afternoon at the airport area. Times are local times.

Figure 4: Map of airport showing the locations of weather stations (green/black circles) and buoys (green/black squares), as well as selected locations of the waterspout derived from SRL data (red/black circles with times (hhmmss) in UTC).

3.4 Fine-resolution numerical weather prediction (NWP) model

Output from a fine-resolution numerical weather prediction model, the Aviation Model (AVM; Chan and Hon, 2016a) was analyzed for this case. The AVM is a 200-m resolution implementation of the Weather Research and Forecast (WRF; Skamarock and Klemp, 2007) model, that possesses positive skill in reproducing a variety of complex meso- and micro-scale airflows around HKIA under real-time settings (Chan and Hon, 2016b; Hon, 2020), including rotating convective storms (Hon et al., 2019; Hon et al., 2021).

4 Data analysis technique summary

Four analyses, briefly described below, were performed on the data.
4.1 Single-Doppler analysis

The Geographical Unified Radar Utility (“GURU”) software tool was used to objectively determine vortex location, diameter and strength using the LIDAR Doppler data directly \( (*\text{Wurman et al., accepted}) \). Automatic/objective vortex center and diameter determinations are augmented through subjective corrections as necessary.

4.2 GVBTD

The Ground Based Velocity Track Display (GBVTD) single Doppler analysis technique \( (*\text{Lee et al., 1999; Lee and Wurman, 2005}) \) was used to retrieve an axisymmetric profile of the tangential winds as well as secondary circulation (radial and vertical winds) as a function of distance from the center of the vortex and height. The axisymmetric (azimuthal averaging) assumption reduces the retrieved strength, especially for non-symmetric vortices.

4.3 Time-to-space conversion (TSC)

Time to space conversion, using the propagation velocity of the vortex, was conducted on surface weather station data in order to produce pseudo-transects. Data from the surface weather stations were converted to locations at 1-second intervals.

4.4 Dual-Doppler analysis

Dual-Doppler analysis of the LIDAR data was conducted using the OPAWS software \( (*\text{see Appendix A of Kosiba et al., 2013}) \). Data were objectively analyzed to a Cartesian grid using 2-pass Barnes analysis \( (*\text{Pauley and Wu, 1990; Majcen et al., 2008}) \). Barnes smoothing parameters were chosen based on the coarsest spatial resolution at the area of interest from the LIDARs. The specific details of each dual-Doppler analysis are presented later with the results of each. All dual-Doppler analyses were two-dimensional, using one sweep from each radar matched as closely as possible in time and vortex data height. All used a minimum allowable beam crossing angle of 30 deg.

5 Analysis and discussion

5.1 Single Doppler analysis

Fig. 5 shows the strength of the waterspout as defined by the difference in wind speed \( (*\text{DV}) \) across the diameter of maximum winds \( (*\text{XD}) \) as a function of time. Fig. 6 shows the track overlaid on a map of the airport. The waterspout becomes stronger and narrower with time until it leaves the coverage area of the SRL at a range of 3 km. The maximum wind an observer on the ground might experience \( (*|Vg|) \) is estimated to be \( DV/2 + \text{speed of propagation} (V_P) \) \( (\sim 10 \text{ m/s}) \). At this time, the waterspout was moving directly away from the SRL, so the raw radar maximum outbound Doppler wind data \( (*V_D) \) can also be used directly to estimate the maximum wind. The waterspout’s maximum outbound \( V_D \) was just over 9 m/s just prior to exiting the SRL domain.

5.2 GVBTD analysis

The SRL data were at an elevation angle of 5 degrees, which corresponds to data that ranges in height approximately 150 m to 220 m AGL at the range of the vortex. Therefore, no information about the vertical variation of the horizontal winds is available. However, an estimate of the vertical wind \( (*W) \) can still be made by assuming no vertical variation in the divergence field.
Figure 6: GURU-derived track of waterspout (black dots) using SRL data as it moves toward the northwest from about 07:51 to 08:18. The waterspout leaves SRL coverage at the NW end of its track when it is strongest. There is evidence of residual observational jitter in the NW part of the track.

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\frac{d^2 V}{ds \, dz} = 0, \quad \text{where} \quad s \quad \text{is horizontal distance and} \quad z \quad \text{is vertical distance} \]

and integrating with respect to \( z \). Vortex centers were determined using GURU and adjusting objectively determined centers as necessary. Data were interpolated onto a Cartesian grid with spacing of 12 m.

Fig. 7 shows the axisymmetric three-dimensional vortex structure as a function of radius. Only a few representative plots of the GBVTD results are shown since 60 independent data times were analyzed. Both \( DV \) and \( XD \) can be derived from GBVTD, and should be similar to those determined using GURU, but with \( DV \) being slightly weaker due to the axisymmetric assumption and smoothing related to interpolation to the Cartesian grids. The derived \( DV \) and \( XD \) are shown as a function of time in Fig. 8. The time variation of \( VT, VR, \) and \( W \) is illustrated in a Hovmöller diagram (Fig. 9). It can be seen that the radius of the vortex is in generally decreasing with time, as shown in the maxima of tangential velocity and the inflow (radial velocity). The figure nicely summarizes the temporal evolution of the radial structure of the vortex with time.

The waterspout was anticyclonic and \( VR \) is directed toward the center outside the RMW throughout the observation period.

5.3 Time to space conversion

Time-to-space conversion (TSC) of surface wind data relative to the vortex centers was complicated in this case by the non-constant \( VP \) of this waterspout. For this case, 2nd order polynomials, varying piecewise over time, were used to calculate and adjust for vortex center locations and \( VP \) for all surface station observing times. The resulting locations of data were plotted on an objectively analyzed map of Doppler velocity as seen by the SRL. Unfortunately, the closest approach to a surface station (R2E) was just before the developing circulation entered the SRL domain. Yet, as seen in Fig. 10a, some curvature of the flow is revealed, and a maximum wind speed of 7.6 m/s was recorded by station R2E. TSC analysis shows the larger scale windshift line (Fig. 10b) annotated by a blue dashed line. The radial velocity of the SRL shows that the radial wind is away from the LIDAR at the southern part of the vortex and it is towards the LIDAR in the northern part of the vortex. As such, the vortex is anticyclonic. Fig. 11 shows the time series of wind speed and direction at station R2E, which indicates it was nearly, but not quite, hit by the circulation, not getting within the RMW. The strongest wind occurred after the passage of the waterspout.

Figure 7: GBVTD analyses at select times. Colors show \( VT \) magnitude. Vectors show \( VR \) and \( W \). The tick mark on the right \( Y \) axis represents the height of data. (a) 07:51:18 UTC, just after vortex enters the SRL observational domain. The RMW can be seen to be about 300 m and maximum axisymmetric wind intensity \( VT \) about 4.5 m/s. (b) 07:56:28 UTC as the vortex weakened. (c) 08:17:54 UTC near time of maximum observed vortex intensity within SRL observational domain.
5.4 Analysis of long-range LIDAR data

The two LRLs, HKG1 and HKG2, also sampled the waterspout, as well as the windshift line, and even other weaker vortices that formed along the same windshift line. With three LIDARs it was possible to conduct dual-Doppler analyses over almost the entire airport. While the waterspout did not directly impact any surface weather stations, two other vortices did, such that the measured wind speeds increased, then decreased as the calmer centers passed, accompanied by pronounced wind shifts. These two encounters were within the dual-Doppler lobes of HKG1 and HKG2. The waterspout, as well as a vortex to its northeast and the windshift line, were within the dual-Doppler lobe of HKG2 and the SRL, allowing an examination of the vortex/windshift line interaction. In fact, the waterspout was only the strongest of several vortices along the windshift line as it passed over the airport grounds from east to west. TSC plots were also produced within the dual-Doppler analyses allowing direct comparison of surface winds with LIDAR-derived winds.

Due to the poorer resolution of the LRLs (gate spacing of 100 m vs 30 m for the SRL), no GBVTD analyses were attempted on the waterspout, but GURU-derived histories of $X_D$ and $DV$ were plotted. Fig. 5 compares the values derived from SRL data with LRL data, showing good agreement except during the period of reorganization when the SRL vortex couplet was dominated by the larger parent structure rather than the smaller vortex.

5.5 Dual-Doppler analysis

The vortices were sampled by the SRL and the two LRLs, with geometry that enabled dual-Doppler analysis. Three domains of the dual Doppler analysis are shown in Fig. 12, along with tracks and labels identifying the vortices discussed below. SRL, HKG1 and HKG2 data were used for the two-dimensional dual-Doppler analysis following techniques described in Kosiba et al. (2013).

Domain C covered the waterspout (vortex “W”) and the Doppler data were objectively analyzed to a Cartesian grid with the following specifications:

- Horizontal grid spacing 20 m.
- Barnes smoothing parameter (kappa) = 0.018 km$^2$ based on the gate spacing of HKG2 of 100 m.

Smoothing parameter, gamma for pass two = 0.3. (see Macjen et al., 2008)
Figure 10: (a) TSC analysis showing objectively analyzed SRL Doppler speed data at 07:52:47 (colors m/s) and wind data from stations R2C, R2E and R2W in knots for better speed resolution. Times indicate when the data were measured (hh:mm:ss). The white circle shows the ring of maximum waterspout Doppler winds measured by SRL. Data, sampled at 1-s, are thinned to 6-minute intervals for clarity. (b) as (a) but at 08:06:50. The blue line indicates the very approximate subjectively-determined location of the windshift line as inferred from the surface data.

- SRL data was from the 08:06:50 sweep
- HKG2 data was from the 08:06:50 sweep
- \( V_p = (-0.56, 0.56) \) m/s (towards northwest).

Domain A covered the vortex (“X”) impacting weather station R2W in the western dual lobe formed by HKG1 and HKG2. On the other hand, Domain B covered the vortex (“Z”) impacting weather station R1E in the eastern dual lobe of these same LIDARs.

For the A and B domains, the objective analyses were conducted on Cartesian grids with the following specifications:

- Grid spacing 10 m.
- Barnes smoothing parameter (kappa) = 0.018 km\(^2\) based on the gate spacing of 100 m.
- Smoothing parameter, gamma for pass two = 0.3.

For Domain A, HKG1 data was from the 08:49:07 sweep and HKG2 data was from the 08:49:01 sweep. The \( V_p = (-2.5, 0.3) \) m/s. For Domain B, HKG1 data was from the 07:56:21 sweep and HKG2 data was from the 07:56:45 sweep. The \( V_p = (-1.0, 0.3) \) m/s. In each case, small offsets (< 5 deg) were applied to the LIDAR headings to better match the vortices’ locations observed by each LIDAR. Applied corrections were varied for each scan.

The dual-Doppler analyses for Domain C, including the waterspout and a weaker vortex (“V”) nearby to the northeast, are shown in Fig. 13. Dual-Doppler analyses reveal the windshift line, which is broken into segments by the waterspout and vortex V. Variations in wind speeds were observed on either side of the windshift line. Regions of stronger winds were observed, but with no discernable pattern. Dual-Doppler winds associated with the waterspout are generally consistent with the surface wind observations from R2E anemometer based on TCS conversion. The waterspout and vortex V are resolved in the dual Doppler analysis. The vertical vorticity associated with each vortex is also shown.

Surface weather station R2W was directly impacted by cyclonic vortex X (which had earlier passed over the terminal building between the long-range LIDARs) and is shown in Fig. 14. This vortex was larger and well resolved, but more complex in shape. Maximum Doppler winds in the vortex at that time were 8 m/s, while the weather station measured a maximum 3-second gust of 10 m/s. The measured wind speed by R2W anemometer shows a dip at the passage of the vortex and the associated change of wind direction (Fig. 15). Dual-Doppler and TSC analyses differed somewhat, likely due to differences between the level of observation contributing to the dual-Doppler analysis and the level of surface observations. Surface winds near the vortex center seemed to be more radially directed than those revealed in dual-Doppler analyses. Wind speeds and directions are generally consistent. Both dual Doppler and surface weather station wind data suggest the existence of a small-scale windshift line running from just north of the vortex eastward. The vortex seems to be near the point of intersection of this line and the large-scale windshift line running north to south through the area. Coverage of the dual-Doppler analysis in this area is limited, making the extent and impact of this line difficult to ascertain.

Another small vortex, Z, which was anticyclonic, crossed almost directly over surface weather station R1E according to a TSC analysis of the dual-Doppler winds, causing a peak 1-second gust of 10 m/s (9.5 m/s maximum 3-second gust) and directional shift of 180 degrees (Figs. 16 and 17). The maximum observed Doppler wind speed in this vortex from either LIDAR was 4.7 m/s; well below the peak observed by the surface weather
Figure 11: Time series of wind speed and direction at station R2E during the nearby passage of the waterspout (red line).

Figure 12: Map showing dual-Doppler domains. Domains A and B use HKG1 and HKG2, while Domain C uses HKG2 and the SRL. Weather stations R2W and R1E were directly impacted by different vortices, labeled with black letters, with approximate paths shown as black curves. The one passing through the red/black circles with times in Domain C is the waterspout, vortex W. All vortices moved generally from east to west along with the north-east to south-west oriented windshift line. Of interest is that vortices X and Y with DV up to 14 m/s, passed over terminal buildings.

5.6 Horizontal Shearing Instability analysis

To evaluate whether horizontal shearing instability (HSI) may have contributed to vortex formation, simplifications of the Rayleigh \( (\frac{\partial^2 \bar{u}}{\partial y^2}) \) and Fjortoft \( [(\bar{u} - u_I)\frac{\partial^2 \bar{u}}{\partial y^2}] \) instability criteria were used (e.g., Mulholland et al., 2017; Kosiba et al., 2020). These were evaluated along a one- to two-km line perpendicular to the vortex line. The component of the wind field parallel to the vortex line (U) at each point was averaged over a perpendicular distance of 500 m to obtain a Ubar for each point along the line. Plots were made of Ubar – U_I, \( d^2\text{Ubar}/d\text{Y}^2 \), and (Ubar – U_I) * \( d^2\text{Ubar}/d\text{Y}^2 \), where Y is the distance along the line, and U_I is the value of Ubar at the inflection point (Figs. 18 to 20). There were not strong signals for the instability criteria, in particular outside of the vortices, suggesting that HSI may have had a small, if any, influence on vortex genesis. But the signal was highly variable from domain to domain. In domain C, for example, there was a stronger signal in association with the waterspout, suggesting that HSI had a role in vortex formation. It is likely that there were other mitigating environmental factors that may be more influential, such as downdraft/updraft interactions.

5.7 Numerical simulation results

Simulation results from the real-time model run of the AVM, initialised at 06:00 UTC on 25 September 2020 (~2 to 2.5 hours ahead of the event) are shown in Figs. 21 and 22. The top panel of Fig. 21 shows the predicted surface wind distribution around HKIA valid at 08:00 UTC. A windshift line, likely induced by convergence of the sea breeze with the prevailing background winds, is clearly seen near the northeast corner of the airport island following a largely meridional (north–south) orientation. Along this line there appear to be various possible centres of rotation, although these tend to be cyclonic rather than anticyclonic. To allow

station. Some of this difference may be due to the comparatively poor resolution of the LIDAR. Dual-Doppler analysis did not resolve this vortex as well as those previously discussed due to its smaller size, but did show the windshift line and a stronger, cyclonic vortex to its northwest, which a short time later passed over the terminal building. Again, the surface station windshift was more abrupt than that shown by the dual-Doppler analysis.
Figure 13: Dual-Doppler analysis valid at 08:06:50 UTC (left) and concurrent Doppler data (m/s) from SRL in Domain C, using HKG2 (origin) and SRL to lower right of plot. Wind speeds (knots) colors, and wind vectors are plotted. Vorticity, blue contours (negative dashed), from $-0.04 \text{s}^{-1}$ incremented by $-0.02 \text{s}^{-1}$. The blue lines are the subjectively-determined location of the windshift line, broken by vortices. The waterspout is the stronger vortex ("W" in Fig. 12) near (0.9, 1.6) with vortex V to its northeast. TCS conversion of wind data (knots) from station R2E every 4 minutes. All distances are in km.

Figure 14: Dual-Doppler analysis in the vicinity of vortex X, valid at 08:49:05 UTC (left) and concurrent Doppler data (m/s) from HKG2 in Domain A, using HKG2 (at origin) and HKG1 to lower right of plot. Wind speeds (knots) colours, and wind vectors are plotted. Vorticity, blue contours, dashed negative, from 0.04 s$^{-1}$ incremented by 0.02 s$^{-1}$. Blue lines are the subjectively drawn location of the windshift line, broken by the vortex. TCS conversion of wind data (knots) from stations R2C and R2W every 2 minutes. All distances are in km.
Figure 15: Time history of wind speed (left) and direction (right) as vortex X passed over station R2W in the A domain. The red line is the time of minimum speed, presumably the moment the station was closest to the centre. The total wind shift is about 180 degrees with the passage of the vortex. The shaded region is when the station is within the radius of maximum winds.

Figure 16: dual-Doppler analysis valid in the vicinity of vortex Z (center) and Y, top, at 07:56:30 UTC in Domain B (left) and concurrent Doppler data (m/s) from HKG2 using HKG2 (at origin) and HKG1 to lower left of plot. Speeds (knots) colours, and wind vectors are plotted. Vorticity, blue contours, negative dashed, from 0.04 incremented by 0.02 s⁻¹. Blue lines are the subjectively-determined locations of the windshift line, broken by the vortices. TCS conversion of wind data (knots) from stations R1E and A1E every 2 minutes. All distances are in km.

a better appreciation of the flow features above ground level, the bottom panel of Fig. 21 displays the simulated LRL return in the form of a 3-degree elevation planar scan. It can be seen that just northeast of the airport island, at a location corresponding to the line of windshift, there are signs of possible rotation in the form of collocated couplets of green and brown. The intensity of these dipoles is clearly much weaker than that analysed from LRL observations. This may be due to the fact that, at 200-m horizontal grid size, the AVM resolution is too coarse to fully resolve and represent the actual small-scale waterspout vortex.

Vertical structure of the simulated vortex is revealed in a cross section along the white line in the bottom panel of Fig. 21. The top panel of Fig. 22 shows the cross section of W. It can be seen that, near the location of the simulated dipole feature, a disturbance with upward motion (positive values in red) surrounding a descending core (downward motion in blue), spanning the altitudes between 500 and 3000 m, occurs in the vicin-
ity of, and above, a low-level rotating feature adjacent to the windshift line. In the bottom panel of Fig. 22, alternating $u$-components (in red and blue) at an altitude below 500 m is suggestive of rotation, while the windshift line due to sea breeze convergence can be seen to its east (right hand side) at an even shallower altitude of $<= 400$ m.

5.8 Summary and conclusions

On 25 September 2020, a windshift line crossed the Hong Kong International airport, spawning a number of vortices, one of which produced a visible waterspout which spent some time on land before heading out over the water and strengthening. Though the vortices were weak, well below criteria for being called tornadoes (Wurman and Kosiba, 2013), the event that day was unusual because it was sampled by three LIDARs and numerous surface weather stations deployed across the airport. The waterspout passed through the dual-Doppler lobe of the short-range LIDAR and a long-range LIDAR, allowing for dual-Doppler analyses. Weaker vortices along the windshift line were also within dual-Doppler lobes of the short and long-range LIDARS. Notably, two of the vortices directly hit two of the weather stations allowing for a rare comparison of radar and ground-based (in situ) direct observations of vortex winds recorded at 1-second intervals.

The waterspout, which was anticyclonic, attained a maximum recorded (by LIDAR HKG2) DV of 21 m/s while passing over the water. At this time, the waterspout was briefly moving northward, directly away from the LIDAR, so the maximum ground-relative wind was equal to the maximum outbound Doppler wind of 11.3 m/s. The diameter of the vortex was at its narrowest at this time too, about 50 m. A comparison of DV and diameter as derived from HKG2 and from the short-range LIDAR showed good agreement except when the wind field of the waterspout appeared disorganized leading to difficulty discerning the vortex center. GBVTD analysis using the SRL data indicated radially inward winds outside the waterspout during its development.

Dual-Doppler analysis was performed for other small vortices appearing along the windshift line. The vortices showed up well in the data, though there were various degrees of agreement with the surface observations based on TSC conversion with wind intensities at the surface stations exceeding Doppler wind measurements in the cases of a direct impact.

The present case of waterspout occurs when there is a wind-shift line and the vortices along this wind-shift line are probably uplifted by updraft associated with convection. The formation process is similar to some previous studies, e.g. Wakimoto and Lew (1993) and Brady and Szoke (1989), also summarized in Miglietta (2019). In particular, in Brady and Szoke (1989), the possible formation mechanism of the non-mesocyclonic tornado is described in its Figure 9, and the process is believed to be very similar to the present case as well. The thunderstorm-related tornado case as reported, e.g., in Van den Broeke et al. (2015), may not be applicable to the present case. It is noted that anticyclonic waterspout is reported in Sugawara and Kobayashi (2008) along a wind-shift line, and the formation mechanism is very similar to the present case as well.

The capability of a fine-resolution numerical weather prediction model in simulating the windshift line and tiny vortices is studied. Simulations hint at the occur-
Figure 18: Top dual-Doppler map from domain C at 08:06:50 showing A–B lines used to calculate HSI quantities. Other plots are derived from the 0.5-km wide area along the line passing through the vortex line. Plot panel A, $\mathbf{U}_{\text{bar}} - \mathbf{U}_{\text{i.B}}$, $\frac{\partial^2 U_{\text{bar}}}{\partial Y^2}$, $\mathbf{C}$, $(\mathbf{U}_{\text{bar}} - \mathbf{U}_{\text{i}})\frac{\partial^2 U_{\text{bar}}}{\partial Y^2}$ on the line passing through the waterspout. Plots D, E and F are as A, B and C, but on the line passing between vortices. The red lines mark the location of the inflection point and the blue lines denote the zero line for the instability parameters. The shaded red region in C and F highlights the area where Fjortoft’s instability criterion is satisfied (or not in plot F).

The presence of the vortices, though the sense of rotation is cyclonic instead of the observed anticyclonic, and the intensity of the simulated waterspout is much weaker than that observed, possibly as a result of insufficient horizontal resolution. The location of the predicted wind-shift line is generally consistent with surface weather observations.

Additional cases of waterspouts in Hong Kong should be analyzed with the aim of generating statistics showing the characteristics of waterspouts in this part of the world, which would have many useful applications such as developing vertical wind profiles for wind engineering and safety purposes.
Figure 19: Top dual-Doppler map from domain A at 08:49:05 showing A–B lines used to calculate HSI quantities. Other plots are derived from the 0.5-km wide area along the line passing through the vortex line. Plot panel A, $U_{bar} - U$, B, $d^2U_{bar}/dY^2$, C, $(U_{bar} - U_j) * d^2U_{bar}/dY^2$ on the line passing through vortex X. Plots D, E and F are as A, B and C, but on the line not passing over the vortex. The red lines mark the location of the inflection point and the blue lines denote the zero line for the instability parameters. The shaded red region in C and F highlights the area where Fjortoft’s instability criterion is satisfied.
Figure 20: Top dual-Doppler map from domain B at 07:56:30 showing A–B lines used to calculate HSI quantities. Other plots are derived from the 0.5-km wide area along the line passing through the vortex line. Plot panel A, $U_{bar} - U_i$, B, $d^2U_{bar}/dY^2$, C, $(U_{bar} - U_i)d^2U_{bar}/dY^2$ on the line passing through vortex Z. Plots D, E and F are as A, B and C, but on the line passing between vortices. The red lines mark the location of the inflection point and the blue lines denote the zero line for the instability parameters. The shaded red region in C and F highlights the area where Fjortoft’s instability criterion is satisfied.
Figure 21: Forecast surface wind distribution in the vicinity of HKIA (top) valid at 08:00 UTC based on the real-time model run of the AVM initialised at 06:00 UTC on 25 September 2020. The simulated Doppler velocity based on the location of LRL HKG-2 using the same AVM model run is shown in the bottom panel.

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