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Observation and numerical simulation of a weak waterspout at Hong Kong International Airport

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Abstract
A weak waterspout was observed at the Hong Kong International Airport on the morning of June 8, 2020. This paper documents the meteorological observations of this weak system, which was well captured by surface wind sensors and a Doppler weather radar, and this study also investigated the capability of a high-resolution numerical weather prediction model to simulate the system in a near real-time configuration. Despite the short-lived nature of the vortex, the model effectively reproduced the occurrence of a weak vortex around the time the system was observed, although with positional errors of the order of a few kilometres. The simulated vertical cross-sections of the reflectivity and Doppler velocity were consistent with the actual radar observations and reflected the slanting nature of the micro-vortex. These results may serve as a useful reference for the study of weak waterspouts worldwide.

KEYWORDS
Doppler, Hong Kong, numerical simulation, waterspout

INTRODUCTION

Waterspouts are relatively uncommon over southern China, including Hong Kong. Based on records from the Hong Kong Observatory (HKO), between 1959 and 2019 only 39 waterspout sightings were reported over Hong Kong waters, representing an average of only 0.64 reported occurrences per year. Previous studies have described waterspouts over southern China in regions neighbouring Hong Kong, such as Zhuhai, which is immediately north of Macao (Chan et al., 2020). While the observation, analysis and numerical prediction of tornadoes are well documented in the literature, particularly over the United States (Doswell III and Burgess, 1988; Stensrud et al., 2009; Childs and Schumacher, 2019; Tao and Tamura, 2020), the arguably less destructive phenomenon of waterspouts has received less study (Golden, 1977; Niino et al., 1997; Devanas and Stefanova, 2018; Rodriguez and Bech, 2018; Miglietta et al., 2020).

The formative mechanisms and characteristics of waterspouts have been documented in a number of classic papers, including those by Bluestein and Golden (1993), Golden (2003) and recently Miglietta (2019). Waterspouts typically form via two main mechanisms: a non-mesocyclonic mechanism with low-level convergence in which the waterspout forms from the water surface upwards and a mesocyclonic pathway similar to that of a tornado in which the waterspout develops from the cloud base toward a water body. In southern China, the mesocyclonic formation pathway appears to be the most common. An example is the waterspout/tornado in 2018 as documented by Hon et al. (2019). In that particular case, a tornado associated...
with a mesocyclone in a thunderstorm situation was discussed. It was rather short-lived (about half an hour) and was a relatively weak system with little damage.

This paper reports the observation of a weak waterspout that occurred over the construction site of a third runway at Hong Kong International Airport (HKIA) on the morning of June 8, 2020. This weather system was well documented by monitoring equipment and reported by local news outlooks (Figure 1). The micro-vortex associated with the waterspout lasted for approximately 15 min based on weather radar observations, and the waterspout formed via a mesocyclonic process in association with a thunderstorm. This short paper documents this waterspout and discusses the performance of a high-resolution numerical weather prediction model in predicting such a weak system. Given the relative lack of detailed studies on waterspouts, it is anticipated that the data and results will serve as a useful reference for weather forecasters worldwide.

2 MATERIAL AND METHODS

A terminal Doppler weather radar (TDWR) was located at Brothers Point (BP), Tuen Mun, around 12 km east-northeast of HKIA. This radar monitors weather conditions in the vicinity of HKIA and provides windshear and microburst alerts in real time. This C-band single-polarisation radar has a dual configuration, in which two systems back each other up to allow high availability. Each system consists of a transmitter, a receiver and a signal processor. The antenna and the antenna servo control are in a single configuration, allowing them to be controlled by either system. The antenna boresight is at a level of around +80 mPD. (mPD is metres above Hong Kong Principal Datum; for general reference, mean sea level is 1.23 m above Hong Kong Principal Datum.) Technical information on the radar is provided in Table 1.

The BP TDWR has two operation modes, monitoring and hazardous, which are selected based on weather conditions. Each volume scan takes 5 min to complete in both modes. When the windshear is relatively low or there is no or only light precipitation, the system operates in the monitor mode; in this mode, each volume scan consists of 14 successive elevations from 0.6° to 23.9°. The two lowest elevation scans, 0.6° and 1.0°, are scanned at a slower speed of 2 rotations per min (rpm), while other elevations are scanned at 4 rpm. When significant rain or windshear occurs around the HKIA, the system automatically switches to the hazardous mode. In this system, scans at 15 elevations from 0.6° to 17.0° are performed at rotational speeds of 4 rpm. The lowest elevation scan is repeated each minute to provide frequent updates on windshear and microbursts.

As the HKIA is situated in a highly dense environment with a high concentration of ships, vehicles and cable cars nearby, TDWR algorithms remove ground and moving clutter, and a hybrid multi-pulse repetition interval method is used to determine radar velocity to represent the velocity field correctly (Yamauchi et al., 2006).

The upper-air winds were recorded by a boundary layer type radar wind profiler at the city centre, which is approximately 20 km to the east of the airport. The wind profiler used a Doppler beam swinging technique to measure three wind components by tracking the emitted electromagnetic waves based on reflectivity discontinuities in the air, such as the boundary between warm and moist air masses and turbulent eddies on hot and sunny days.
In this study, the 200 m grid aviation model (AVM) implement of the HKO Weather Research and Forecast (WRF) model was used to simulate the event. The AVM focuses on fine-scale weather evolutions around the graphically complex HKIA area and has demonstrated the ability to reproduce complex airflow features at mesoscale and microscale under a wide range of weather conditions (Chan and Hon, 2016a; 2016b; Chan et al., 2020; Hon, 2020). At the time of the event, the operational forecast domain of the AVM comprised $581 \times 581$ grid points horizontally, covering an area of approximately $112 \times 112$ km$^2$ centred around HKO. Since HKIA is about 26 km west of HKO, the region of interest was relatively close to the western lateral boundary of the model domain. Real-time model runs were unable to sustain the intensity of the rainfall observed upstream (west) of HKIA. Therefore, an additional run was performed using a large-domain configuration of the 200 m AVM in a manner similar to Hon (2018), the results of which are shown below.

The experimental forecast domain comprised $1,501 \times 1,501$ horizontal grid points covering the area of $20.95–23.65$ °N, $112.46–115.38$ °E. Vertically, there were 60 eta levels, of which at least 10 were configured in the lowest 1 km at the beginning of model integration. Initial and boundary conditions were provided by a real-time run of the 2 km RAPIDS-NHM model, HKO’s operational mesoscale model, initialised at 2200 UTC, June 7, 2020. The RAPIDS-NHM is based on the non-hydrostatic model (NHM) of the Japan Meteorological Agency (Saito et al., 2006). These were used to drive the large-domain AVM forecast, initialised at 2300 UTC, June 7, 2020 (i.e., 3 hr before the event). As with the real-time AVM model runs, only conventional surface and upper-air observations (mainly collected by the dense automatic weather station network over Hong Kong and the inland Guangdong Province) were assimilated in the experimental forecast using the WRF 3D variational assimilation algorithm. Since the 2 km RAPIDS-NHM already employed indirect radar data assimilation in the form of 1D variational temperature and humidity profiles retrieved following Wattrelot et al. (2014), neither the experimental nor the real-time AVM model runs further assimilated radar observations. Instead, hydrometeorological fields (including the mixing ratios of rain, ice and graupel) were determined based on the initial conditions provided by RAPIDS-NHM. Key model configurations include the WRF double-moment six-class microphysics scheme (Lim and Hong, 2010), rapid radiative transfer model (RRTMG) schemes for short- and long-wave radiation (Iacono et al., 2008) and the Noah land surface model (Niu et al., 2011). Given the high horizontal resolution, no cumulus parameterisation and boundary layer schemes were used (the latter is the so-called “large eddy simulation” or LES mode). US Geological Survey 3 s topography and Moderate Resolution Imaging Spectroradiometer (MODIS) land use data were used with local adaptations to represent urbanised areas and coastline changes.

3 | DATA ANALYSIS

3.1 | Synoptic and local weather conditions

The event occurred at approximately 10 a.m. (0200 UTC, HKT = UTC + 8 hr), June 8, 2020. A synoptic surface chart from 8 a.m. (0000 UTC) on that date (Figure 2a) showed that the south China coast was under the influence of a trough, which brought unsettled weather and heavy rain to the region. Based on surface observations near the airport (Figure 2b), south to southwesterly flow prevailed, and a cyclonic signature was observed near the location of the waterspout.

Two surface weather stations were located near the waterspout, namely Z3C and R2C (locations are shown on Figure 2b). The 10 s mean surface wind speeds and wind directions are shown in Figure 3. As the waterspout approached, the wind speed dropped from 10–12 m s$^{-1}$ to just a couple of metres per second. The prevailing wind direction also changed from southsouthwesterly to northnortheasterly winds for a short period. The cyclonic circulation extended from the cloud base to the sea surface.

From the radar wind profiler, around the time of the event (10 a.m., or 0200 UTC), the winds at the boundary layer and the middle troposphere remained generally south to southwesterly, with strong winds occurring only rarely before and after the event (blue wind barbs in

| TABLE 1 | Technical information on the terminal Doppler weather radar |
|---------|----------------|
| **Transmission frequency** | 5,625 GHz |
| Diameter of antenna | 7.9 m |
| Half power beam width | 0.55° |
| Gain of antenna | 49 dB |
| Power | 250 kW (peak) 500 W (average) |
| Pulse width | 1 µs |
| Pulse repetition frequency | 1,380 Hz and 1,104 Hz |
| Range resolution | 150 m |
| Nyquist velocity | $\pm 73.6$ m s$^{-1}$ |
Figure 4a). The vertical windshear was calculated based on the wind profiler measurements and data from a surface wind station just east of the airport (Peng Chau; location shown in Figure 2b) represented the background wind conditions (time series shown in Figure 4b). The vertical windshear between the surface and 1 km remained above the daily mean (i.e., the climatological mean of June 8 during 2010–2020) from the early morning through the afternoon. The same applies to the vertical windshear between the surface and 3 km and the surface and 6 km. Around the time of the waterspout occurrence, the vertical windshear was of the order of $10 \times 10^{-3} \text{ s}^{-1}$, similar to that reported by Chan et al. (2020) and with observations of typhoon-related tornados in southern China (Huang et al., 2020). As reported in previous cases (i.e., tornados in southern and central China), relatively high vertical windshear is suspected to support the occurrence of waterspouts.

A tephigram from 0000 UTC, June 8, 2020, is shown in Figure 5. The radiosonde station was located approximately 1 km south of the wind profiler station in the city centre. The $K$ index was relatively high at approximately 39 K, which was indicative of an unstable atmosphere. The convective available potential energy (CAPE) was
approximately 2,337 J·kg⁻¹, which was also indicative of atmospheric instability.

In past observations of typhoon-related tornados in southern China, CAPE values could be as low as several hundred (Huang et al., 2020). Atmospheric conditions are conducive to the occurrence of thunderstorms. Several temperature inversions were noted in the vertical profile of the atmosphere. Although capping inversions have been reported to precede the development of tornados often in some areas (such as the Midwestern United States), the inversions observed in the present case did not appear to have sufficient magnitude to function as capping inversions. The equivalent potential temperature profile derived from the tephigram is shown in Figure 5b. The equivalent potential temperature profile was rather unstable in the atmospheric boundary layer, which favours the occurrence of intense convection such as that which occurs in thunderstorms.

The storm relative helicity (SRH) for 0 to 1 km as derived from the tephigram was 201 m²·s⁻², much higher than the 2010–2020 climatological mean of 33 m²·s⁻² in June. Moreover, in southern China, tornados associated with typhoons normally feature SRH values exceeding 150 m²·s⁻² (e.g., Huang et al., 2020). The relatively high value of SRH is also indicative of the occurrence of a tornado/waterspout.
The Szilagyi Waterspout Index (SWI) was determined based on radiosonde measurements (Renko et al., 2018). This value is based on sea surface temperature, 850 hPa temperature, lifting condensation level and equilibrium level and assesses the chance of waterspout occurrence based on a nomogram determined empirically from past

**FIGURE 4** Wind profiler observations at Sham Shui Po (a), and the derived vertical windshear based on wind profiler and surface wind measurements at Peng Chau (b). The time is in HKT. The vertical line is the time of waterspout observation.
The sea surface temperature was 26°C, whereas the 850 hPa temperature was 18.9°C, producing a difference of 7.1°C. The lifting condensation level was 1,000 hPa, and the equilibrium level was 234 hPa. The heights of the lifting condensation level and the equilibrium level were 66 m and 11,472 m above mean sea level.
respectively, yielding a height difference of 11,406 m or 37,421 ft. The waterspout fell within the category of thunderstorm-related waterspouts in the Szilagyi Waterspout Nomogram, and the SWI was approximately 5, both of which suggested the occurrence of a waterspout. However, more observations must be collected to determine the applicability of the SWI to southern China.

### 3.2 Weather radar observations

The BP TDWR was operating in the hazardous mode when the waterspout appeared. Figure 6 shows a radar image taken when the waterspout was close to HKIA. A Doppler velocity couplet appeared at $-48 \text{ m} \cdot \text{s}^{-1}$ in the area of the strong negative velocity and at $-4 \text{ m} \cdot \text{s}^{-1}$ in a

![Figure 6](image-url)
region with weaker inflow, and the radar reflectivity was relatively high—over 40 dBZ. A vertical cross-section was generated across the micro-vortex associated with the waterspout, and the resulting images are shown in Figure 7, in which the slanting core of the Doppler velocity and the micro-vortex reflectivity are clearly visible. This slanting feature was also reported by Chan et al. (2020); however, the physical reasons for the slanting feature have not yet been confidently determined. Slanting during the intensification phase of tornados has been reported in the literature (e.g., Bluestein et al., 2019). In this scenario, the slanting is considered to represent a misalignment between the mid- and low-level mesocyclones. This misalignment is believed to enhance the stretching (increasing the length of the vortex and tilting it onto the horizontal) and intensification of the pre-existing vortex, thus amplifying tornadogenesis. However, more observational studies are required to determine whether such slanting features are common in vortexes in southern China.

The time series of the maximum positive Doppler velocity and the maximum negative Doppler velocity of the micro-vortex associated with the waterspout are shown in Figure 8a. The latter was larger because of the background southsouthwesterly flow. Only the values at the lowest two elevation angles, namely 0.6° and 1°, were considered, and these values did not exhibit large changes during the event. At three points the maximum positive Doppler velocity was higher, as indicated by the arrows in Figure 8a.

The difference between the maximum outbound and maximum inbound Doppler velocities as a function of time and height is shown in Figure 8b. Relatively high initial maximum shear values, for example 41–50 kn, generally decreased with time apart from a short period between 0942 and 0944 local time (0142 and 0044 UTC). An increase in the maximum shear was also observed from 0950 to 1000 local time (i.e., 0150 to 0200 UTC). The descending maximum shear may be indicative of micro-vortex development toward the ground.

The vertical profiles of the Doppler velocity for the three indicated times in Figure 8a are shown in Figure 9. In general, the maximum negative Doppler velocity steadily increased with height. The vertical profiles were generally consistent with those reported in Chan et al. (2020); however, the limited number of documented samples makes it difficult to establish whether the vertical profile of the wind reflects those typically associated with waterspouts/tornados over southern China. More samples should be collected to determine typical vertical wind profiles, which have many potential applications, such as engineering tall buildings to withstand winds in southern China or the development of policies to ensure severe-weather preparedness.

4 RESULTS

The results of the experimental run are shown in Figures 10–12. The left column of Figure 10 compares the simulated radar reflectivity at two different zoom levels to the TDWR observations at 0149 UTC (0949 local time). The simulated radar reflectivity fields were calculated following RIP software protocols (Stoelinger, 2018) in which
the equivalent single-polarisation radar reflectivity factor (in dBZ) at each model grid was derived based on hydrometeor mixing ratios (but not number density) for the available species in the WRF output (including rain, snow and graupel), assuming spherical, constant-density particles with exponential size spectra. It is understood (and accepted) that there are various known deficiencies under such a simplified approach to the computation of dBZ values, including microphysical properties of ice and mixed-phase hydrometeors as well as assumptions regarding the electromagnetic scattering regime (using only Rayleigh and not the Mie regime). However, it is stressed that here the dBZ value is a diagnostic parameter whose errors do not in any way affect the simulated dynamics and structure of the rotating storm under study. For more quantitative applications such as reflectivity assimilation, a more rigorous approach will certainly be required. The AVM is configured to output data every minute, and data from the output time nearest to 0150 UTC were used. The bottom left panel of Figure 10 indicates that the model run generally reproduced the occurrence of intense radar echoes surrounding HKIA, although the extent of the echoes at 40–50 dBZ (yellow shading) and 50 dBZ or above (red or purple) appears to be over-exaggerated. In the magnified image (top left panel), the occurrence of a small region of slightly weaker echoes directly atop HKIA, in between the more intense echoes around the island, was reproduced in the model forecast. The top right panel shows the simulated Doppler velocity, which was computed by assuming a radar location identical to that of the BP TDWR. In association with the intense echoes simulated immediately east of HKIA, a region of strong negative velocity (inflow) is indicated, while an area of weaker inflow appears a few kilometres to the northwest. Compared to the TDWR observations discussed above, the experimental run

**Figure 8** (a) Time series of maximum positive velocity (orange) and maximum negative velocity (blue) at the lowest elevation angles (0.6° and 1°) and the three time points shown in Figure 9. (b) Difference between the maximum outbound and maximum inbound Doppler velocities as a function of time and height. The times are in HKT. The waterspout time is indicated by a purple vertical line.
simulated a velocity couplet like those associated with a micro-vortex, although the simulated location appears to be shifted 5–10 km from just north of HKIA to its east.

Figure 11 shows the cross-section made along the dotted line in the top right panel of Figure 10. This line was chosen for its near perpendicular orientation to the Doppler velocity couplet shown in Figure 10. The top panel is the Doppler velocity cross-section. Given the strong negative values generally observed due to active southwesterly winds (which inflow towards the BP TWDR relative to HKIA), an adjusted colour scale was used to highlight the alternating couplet values. In the highlighted area, a vertical streak of most intense negative values (deep blue; up to $-30 \text{ m}\cdot\text{s}^{-1}$) appears adjacent to a streak of much less intense velocities (white to light red; between $-20$ and $-18 \text{ m}\cdot\text{s}^{-1}$). This velocity couplet extended from a height of 3–4 km to about 200 m above the surface, although there was some tilting in its vertical structure. In the bottom panel, the simulated velocity couplet appears to collocate well with the descent of an intense column of simulated reflectivity toward the surface from a height of 3–4 km. Together, these plots suggest that the salient TDWR signatures of the micro-vortex associated with the observed waterspout were successfully reproduced in the experimental run, albeit with a horizontal phase error. In particular, the slanting of the micro-vortex core was well captured by the model simulation.

Finally, Figure 12 presents another cross-section along a north–south orientation (top panel) in accordance with the BP TDWR observations. Again, tightly packed alternating columns of negative Doppler

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**FIGURE 9** Vertical profiles of maximum negative velocity (left panels) and maximum positive velocity (right panels) for the three time points indicated by arrows in Figure 8a
velocities (middle panel) appear to collate with the descending radar reflectivity column towards the surface. In Figure 12, the velocity couplet again failed to reach the sea surface, remaining 200–400 m above sea level. In this orientation, the simulated column of the radar signature appears to extend upward to a height of 4,500 m or above, which corresponds well with the height observed in the BP TDWR scans. Based on some earlier observational studies including dedicated airborne remote-sensing instruments (Schwiesow, 1981; Schwiesow et al., 1981), the horizontal resolutions of both the TDWR and the sub-kilometre AVM of the HKO cannot fully reflect the microscale airflow and hydrometeorological properties of a waterspout. Nonetheless, the above results demonstrate the capacity of a high-resolution NWP model in predicting the salient features of a weak system with a substantial lead time.

However, as mentioned earlier at the end of Section 2, the corresponding real-time operational run of the 200 m AVM was unable to produce or sustain the

**FIGURE 10** Observed (bottom row) and simulated (top row) radar reflectivity (left column) and Doppler velocity (right column) of the thunderstorm cluster associated with the waterspout. The top right panel shows the corresponding simulated Doppler velocity assuming a radar located in the same place as Hong Kong Observatory’s Brothers Point terminal Doppler weather radar. The black dotted line shows the location of the cross-section in Figure 11, which cuts across the simulated microscale vortex corresponding to the waterspout. In both the observed and simulated radar reflectivity distributions, a small region of relatively low reflectivity can be seen over Hong Kong International Airport (white dotted circles; top left and bottom left panels).
convective system associated with the observed waterspout, despite the otherwise identical model configurations. Referring to the preceding sections, the only difference in the experimental model run was the domain size. Considering the capability of the experimental run (as shown above) in reproducing the salient features of the waterspout-related system, a key factor may have been the better inclusion spatially of the upstream convection within the larger model domain, which happened to span the western lateral boundary of the smaller operational domain and hence was adversely affected. Through a comparison of the 3D structure of the simulated convective system against radar observations and literature accounts, it appears that the 200 m WRF configuration adopted in the AVM, including the selection of physical parameterisations,
was otherwise appropriate for the simulation of mesoscale, organised convection.

Globally there are various efforts in improving the real-time prediction of rotating convective storms. A notable example is the Warn-On-Forecast initiative in the United States (Stensrud et al., 2009) which uses rapidly updated convection-permitting ensemble prediction and assimilation systems. Such a large-scale undertaking, while commensurate with the frequent occurrence, and associated magnitude of damage, of tornadic storms over the North American continent, is easily beyond the level of resources available to smaller or regional meteorological agencies in other parts of the world. In Hong Kong, it is perhaps fortunate that waterspouts or tornados, despite being capable of generating considerable public interest, are so far rarely known to cause casualties or property...
damage, making their prediction a less pressing issue in terms of service or operational needs. It is hoped that this study can serve to document and benchmark the current capability of a high-resolution (sub-kilometric) deterministic model in predicting such weather systems in a near real-time manner, potentially offering a cost-efficient technical alternative to the computationally demanding ensemble-based methodology.

5 | CONCLUSIONS

A relatively weak waterspout in Hong Kong is documented in this paper. The circulation of the waterspout overlaid on the background southwesterly flow gave a maximum velocity of approximately 30 kn. From the radar data, the delta velocity was of the order of 50–60 kn. Two anemometer stations near the waterspout have recorded circulation around its centre. The waterspout is associated with a thunderstorm, belonging to the mesocyclonic type in the literature. There is a meso/micro-cyclone in the atmosphere, and the maximum shear extends downwards towards the sea surface.

Discussions of waterspouts in southern China are not abundant in the literature. In the Chinese literature there are some discussions about tornadoes over southern China in association with typhoons, such as the summary in Huang et al. (2020) and the references therein. This paper summarises the environmental conditions associated with the waterspout, such as convective available potential energy, storm relative helicity and vertical windshear. More waterspout cases would need to be accumulated in order to determine the “climatology” of environmental conditions for waterspouts in southern China.

The micro-vortex associated with the waterspout is well captured by the terminal Doppler weather radar. Similar to previous observations, a slanting core of reflectivity and velocity was observed. The vertical profiles of the maximum negative velocity are also consistent with previous observations. Such information would be useful for wind engineering applications for buildings in southern China.

The capability of a high-resolution numerical weather prediction model in the simulation of the waterspout is examined. In an experimental run using a larger forecast domain encapsulating the initiation location of the parent storm, the 200 m resolution model is able to capture the occurrence of the micro-vortex associated with the waterspout, although it is rather short lived in the simulation, lasting of the order of 10 min or so, and with a location error of a few kilometres. The vertical cross-sections of the simulated reflectivity and velocity are consistent with the actual observations. It is hoped that this study could serve to document and benchmark the current capability of a high-resolution (sub-kilometric) deterministic model in predicting such weather systems in a near real-time manner, potentially offering a cost-efficient technical alternative to the computationally demanding ensemble-based methodology pioneered and advocated in other parts of the world.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

ETHICS APPROVAL STATEMENT

Not applicable.

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