NUMERICAL SIMULATION OF VORTEX SHEDDING OBSERVED AT THE HONG KONG INTERNATIONAL AIRPORT USING A SHALLOW WATER MODEL

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Abstract: The Hong Kong International Airport is situated in an area of hilly terrain, with a number of hills to its northeast and on the mountainous Lautau Island to the south. In a stably stratified boundary layer, vortices shed by these hills are sometimes observed by the Terminal Doppler Weather Radar (TDWR) and the Doppler LIght Detection and Ranging (LIDAR) System operated by the Hong Kong Observatory. They have a length scale of at least several hundred metres and occur with a shedding period of 15 to 45 minutes. This paper uses a single-layer shallow water model to simulate the vortex shedding events observed in two wind regimes, namely, an easterly wind case on 19 January 2005 and a northeasterly wind case on 27 January 2002. The model wind field (resolved along the mesaurement radials of TDWR and LIDAR) and the vortex shedding periods in the simulations were found to be largely consistent with the TDWR and LIDAR observations. Though the dynamical equations are simplified and there is a single layer only, the shallow water model appears to grasp the basic dynamics of the observed shedding events

Keywords *– vortex shedding, shallow water model, Doppler LIDAR, Terminal Doppler Weather Radar*

1. INTRODUCTION

The Hong Kong International Airport is located in a hilly environment (Figure 1). There are a number of hills to its north (up to about 600 m in height) and on the mountainous Lautau Island to the south (with peaks rising to nearly 1000 m). The airflow may become disturbed after passing over the hills under certain meteorological conditions and lead to windshear and turbulence which could affect aircraft operating at the airport. To monitor the winds, the Hong Kong Observatory (HKO) operates a suite of weather sensors inside and around the airport, including anemometers, TDWR and LIDAR (locations in Figure 1).

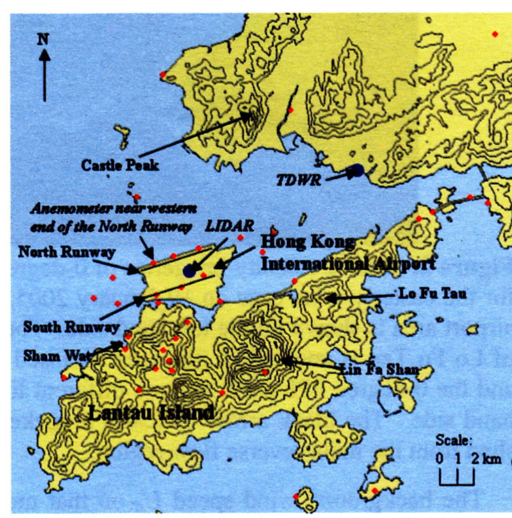


Figure 1. Map of the Hong Kong International Airport and the adjacent areas. Height contours are in 100 m. Red dots are the surface cup/vane-anemometer stations operated by the Hong Kong Observatory.

One form of disturbed airflow observed at the airport region is the shedding of vortices from the hills. This phenomenon has been studied for tropical cyclone situation in summer (Shun et al. 2003). Vortex shedding is also observed in stably stratified boundary layer in winter and spring. With easterly or northeasterly winds passing over the mountainous terrain, vortices are sometimes found to shed from the hills as shown in the surveillance scans of TDWR and LIDAR. They have a length scale of at least a few hundred metres and occur with a shedding period of 15 to 45 minutes.

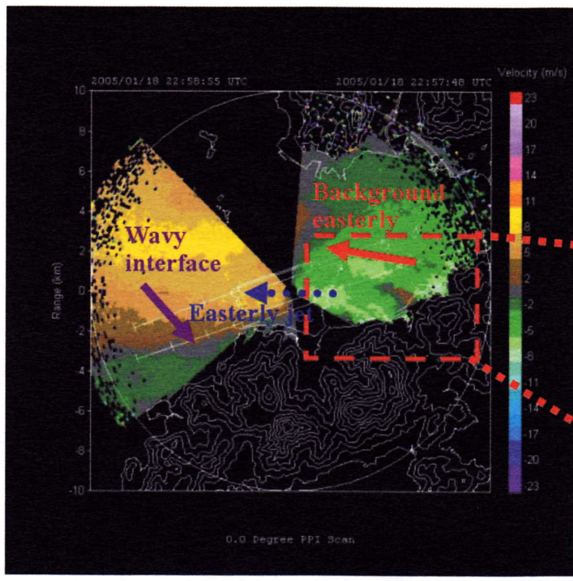
In this paper, the one-layer shallow water model developed by Schär and Smith (1993) is employed to simulate the vortex shedding events in two wind regimes in winter, namely, easterly wind and northeasterly wind. Section 2 introduces the model. Sections 3 and 4 describe the simulation results in these two wind regimes. Conclusions are given in Section 5.

2. SHALLOW WATER MODEL

The shallow water model used in this paper is same as that in Gohm and Mayr (2004), which was originally developed by Schär and Smith (1993). It is based on the two-dimensional governing equations for a single-layer hydrostatic flow without ambient rotation and surface friction. The model domains in this study have a typical length of 20 – 40 km and Coriolis effects could be neglected as a first approximation. The topography of Hong Kong is resolved at a horizontal spatial scale of 90 – 100 m, which provides a good representation of the complicated terrain in the vicinity of the airport. Each model run is made up to 30000 time steps with a step of 0.01 model time.

3. VORTEX SHEDDING IN EASTERLY WIND REGIME

Under the prevalence of easterly winds, vortices are sometimes observed to shed from a hill named Lo Fu Tau with a height of 465 m (Figure 1) towards the waters east of the airport, as depicted in the LIDAR data. For instance, in the morning of 19 January 2005, vortices were found to shed from Lo Fu Tau in the 0-degree plan position indicator (PPI) scans of the LIDAR. The time evolution of a shed pocket is shown in Figure 2. Between 6:51 and 8:05 a.m. (Hong Kong time, 8 hours ahead of UTC) on that day, five such pockets shed from the main reverse flow area, i.e. each pocket has an average shedding period of about 15 minutes. The lengths of the pockets along and across the prevailing wind direction are about the same, generally in the order of 500 m and within the length scale of windshear in aviation which is typically 400 – 4000 m (Proctor et al. 2000).



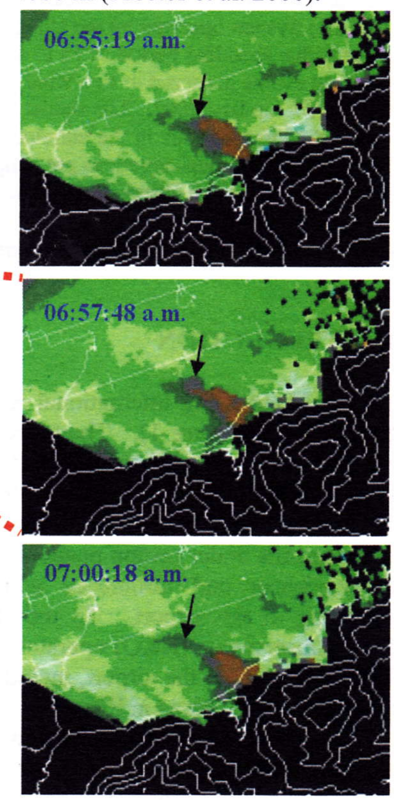


Figure 2. Radial velocity imageries of 0-degree PPI scans of the LIDAR for the easterly wind case on 19 January 2005. The scan over the whole airport area is shown on the left hand side. The reverse flow downstream of Lo Fu Tau is zoomed in (the area enclosed in a red, broken-line box) and the 0-degree PPI scans at three different times are given on the right hand side. The black arrow indicates a pocket of reverse flow that was shed from the main reverse flow region.

The background wind speed U_0 on that morning was about 7 m/s. According to the review by Atkinson (1981), the shedding period (T) could be expressed in terms of the Strouhal number (St) and the dimension D of the obstacle:

$$T = \frac{D}{\mathrm{St}U_0}. \tag{1}$$

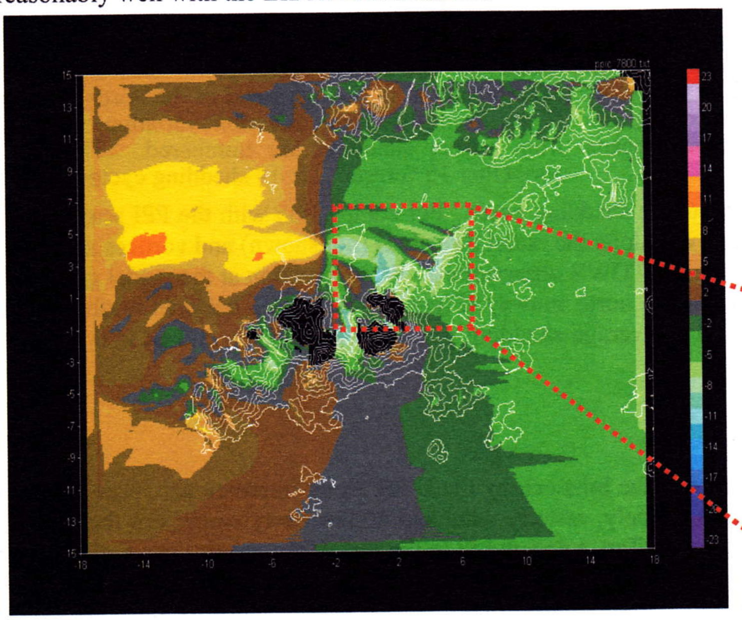
St was found to range between 0.15 and 0.32. Taking D to be 1500 m for Lo Fu Tau, the shedding period of 15 minutes observed by the LIDAR corresponds to St of 0.24, which is consistent with the range given by Atkinson (1981). From the radiosonde measurement at King's Park (located at about 25 km east of the airport) at 8.a.m. on that day, a temperature inversion was found between around 300 and 780 m (not shown), with a mean potential temperature of 291 K and a temperature change of 5 K. The fluid depth is taken to be around 500 m due to a sharp change of potential temperature at this height (not shown). With all these values, the Froude number (Fr) is estimated to be about 0.8. The background wind direction was around 100 degrees.

Numerical simulation with the shallow water model is performed with the above values of Fr, fluid depth and background wind direction. To facilitate comparison with the LIDAR observations, the single-layer wind vectors from the model are resolved along the LIDAR radial directions (Figure 3). The LIDAR radial velocities and the model wind data are found to generally agree on the following broad features of the wind field in the airport area:

(a) accelerated gap flow emerging between Lo Fu Tau and Lin Fa Shan (locations in Figure 1) and extending westwards into the airport;

(b) south to southwesterly wind emerging from Sham Wat (location in Figure 1) and a "wavy interface" in the radial velocity to the west of the airport between this towards-LIDAR airflow and the background away-from-LIDAR easterly wind.

Moreover, in the model simulation, pockets of reverse flow are observed to shed from the main region of reverse flow downstream of Lo Fu Tau. A shedding process is shown in Figure 3 and it appears to be very similar to the LIDAR observations (Figure 2). Based on the time series of the wind speed and wind direction at a model grid point downstream of Lo Fu Tau (not shown), the shedding period is about 13 minutes and St is 0.27, both agree reasonably well with the LIDAR observations.



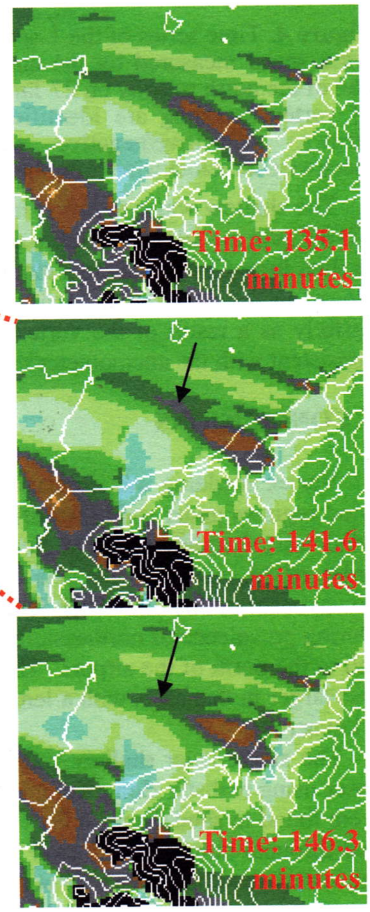


Figure 3. Shedding of a pocket of reverse flow (indicated by an arrow) from the main region of reverse flow downstream of Lo Fu Tau in the shallow water model simulation for the easterly wind case. The model wind vectors are resolved along the radials of the LIDAR. The velocity scale is same as that in Figure 2.

4. VORTEX SHEDDING IN NORTHEASTERLY WIND REGIME

When northeasterly wind prevails over Hong Kong, vortex shedding is sometimes observed to take place downstream of a hill named Castle Peak with a height of 583 m (Figure 1). A shedding case in the morning of 27 January 2002 was studied in detail. It was cloudy to overcast with light rain on that day. The 0.6-degree PPI scans of the TDWR (not shown) provided radial velocities up to more than 30 km away, covering the whole airport and the adjacent regions. They depicted an area of reverse flow to the southwest of Castle Peak and the shedding of pockets of reverse flow from it. The pockets appeared to be elongated along the direction of the prevailing flow with an along-flow length of about 4 km and an across-flow width of about 2 km. These are also within the windshear length scale. They were found to drift generally towards southwest and pass the western end of the airport's north runway. The corresponding wind changes were registered by the anemometer at that location. Between 5:30 and 7 a.m., the wind direction of the anemometer (Figure 4) went through two cycles, changing from easterly through northerly to westerly and then back to easterly again in each cycle. The shedding period of the vortex is about 45 minutes.

The background wind speed was about 6 m/s on that morning. Taking the diameter of Castle Peak to be 3000 m, the shedding period of 45 minutes registered by the anemometer corresponds to St of 0.19, which is within with the range given by Atkinson (1981). The boundary layer was stably stratified from the radiosonde measurement at King's Park (not shown). A temperature inversion was found between 280 and 520 m with a mean potential temperature of 285 K and a temperature change of 2.3 K. The fluid depth is taken to be 400 m. With all these values, *Fr* is estimated to be about 1.1. The background wind direction was 30 degrees.

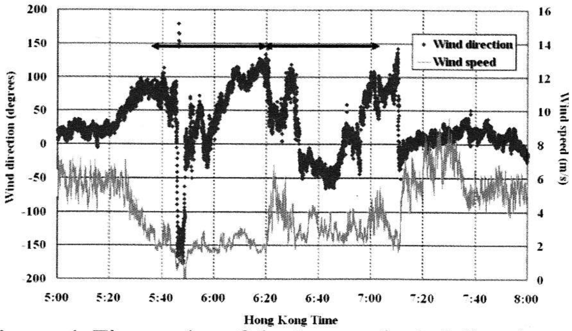


Figure 4. Time series of the 1-second wind direction and wind speed measured by the anemometer near western end of the north runway on 27 January 2002. Two cycles of vortex shedding are identified, as indicated by the arrows. Positive/negative wind direction means clockwise/anticlockwise from the North.

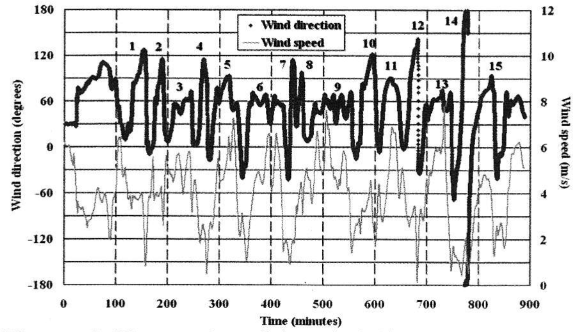


Figure 5. Time series of the wind direction and wind speed at the model grid point closest to the anemometer at the western end of the north runway. "Crests" in the wind direction variation resulting from vortex shedding are numbered. There are altogether 15 "crests", i.e. 14 shedding cycles.

The shallow water model is used to simulate the shedding event. For comparison with the PPI scans of the TDWR, the model wind vectors are again resolved along the radial directions (not shown) and vortices are found to shed from Castle Peak in a manner similar to the TDWR observations. Wind direction at the model grid point closest to the anemometer near western end of the north runway (Figure 5) fluctuates between northerly and easterly as a result of the vortex shedding. The average shedding period is 48 minutes and St is 0.17, both consistent with the anemometer measurements.

5. CONCLUSIONS

Vortex shedding was observed to take place at the hills nearby the Hong Kong International Airport in two wind regimes under stably stratified conditions, namely, easterly wind and northeasterly wind. For the easterly wind case, shedding occurred downstream of Lo Fu Tau, a 465-m hill to the east of the airport, at a period in the order of 15 minutes. Pockets of reverse flow were found to shed from the main region of reverse flow downstream of this hill. Their lengths along and across the prevailing flow direction were of the order of 500 m. During prevalence of northeasterly winds, shedding was observed to occur downstream of Castle Peak, a 583-m hill to the north of the airport. The shedding period was of the order of 45 minutes. The pocket of reverse flow was larger in this case, with a length of about 4 km along the prevailing northeasterly flow and a width of about 2 km across.

The single-layer shallow water model of Schär and Smith (1993) was employed to simulate the shedding cases using realistic Hong Kong terrain (at a horizontal resolution of around 100 m). In the model runs, vortices were found to shed from Lo Fu Tau and Castle Peak in a manner similar to observations. The shedding periods and Strouhal numbers estimated from the model results were consistent with the observed values, even though the vortex shedding events do not appear to resemble the classical Kármán vortex streets. Though the dynamical equations are simplified and there is a single layer only, the shallow water model appears to grasp the basic dynamics of the observed shedding events.

The shed vortices in this study had a size of 500 – 4000 m, which is within the length scale of windshear in aviation. The results from the single-layer shallow water model illustrate nicely the intermittency of terrain-induced windshear and may help quantify the probability of windshear associated with vortex shedding from the hills. Further work would be carried out in this direction.

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