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Towards understanding the impact of convective weather on aircraft arrival traffic at the Hong Kong International Airport

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Towards understanding the impact of convective weather on aircraft arrival traffic at the Hong Kong International Airport

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Abstract. Convective weather (thunderstorm clusters with horizontal extents from tens to hundreds of kilometers, and vertically up to 10 - 15 kilometers in the troposphere) along aircraft flight trajectory is a key factor influencing air traffic management decisions and aviation safety. For an airport, aircraft arrival performance is typically more sensitive to weather conditions than departures. The occurrence of thunderstorms along or around flight routes may force the arriving aircraft to hold/vector in the terminal maneuvering area (TMA) following air traffic control (ATC) instructions, leading to additional fuel burn and delays. Such effects could cascade and bring further negative impacts to air traffic inside TMA. In this work, we perform a joint analysis of high-resolution radar rainfall distribution with 2-D aircraft flight trajectory data surrounding the Hong Kong International Airport (HKIA) to uncover the potential spatio-temporal impact of thunderstorms on air traffic. Results indicate that aircraft arrival traffic is sensitive to the location of convective weather in TMA, which also introduces a time lag effect on subsequent air traffic on the order of hours.

1. Introduction

Despite the recent strict flight restrictions brought about by the Covid-19 pandemic, the aviation industry will continue facing operational challenges pertaining to safety issues, increased demand, and sustainable development from a long-term perspective. This confidence comes from the fact that the aviation industry has demonstrated its resilience in the past, as it always managed to recover after disruptive events such as terrorist attacks, the severe acute respiratory syndrome (SARS) outbreak, and financial crises, to name a few [1]. The current technical and operational limitations can lead to undesirable delays and economic loss. To improve the efficiency of the air traffic management (ATM) system, organizations such as the Federal Aviation Administration (FAA), the International Civil Aviation Organization (ICAO), and Eurocontrol successively launched several new projects (NextGen, ASBU, SESAR) in the late 2010s. One of the common key factors that are emphasized among all plans is the integration of meteorological information into the ATM decision-making process, or "MET-ATM integration".

Weather impacts can affect aircraft performance at every stage of a flight mission. Local weather conditions, for instance, affect the take-off and landing of aircraft. Rain, ice, snow, or hail can prolong runway occupancy time. The onset of thunderstorms causes congestion and reduces airspace capacity, and the associated cumulonimbus clouds affect pilots' visibility, in addition to potentially causing in-flight turbulence from a distance. Even though weather information is so vital to air traffic operation planning and evaluation, there is still a long way ahead for it to become fully and effectively incorporated into existing ATM assessment tools [2]. It is therefore imperative to develop an integrated air transportation analysis and prediction framework that properly takes weather information into account.

To achieve the eventual goal of complete integration between weather information and air traffic operation, the emerging concept of “Aviation Big Data” or “Big Data” has been explored by various researchers recently [3, 4]. With the constant updates provided by state-of-the art detection equipment (such as weather radar, meteorological satellites), there is abundant data that can potentially be utilized to accomplish accurate prediction of the interwoven elements of local weather, air traffic, and airborne time [1, 5]. In this paper, we perform a first study on the integrated analysis of high-resolution aviation-impact weather distribution and aircraft arrival traffic at a major international airport. Section 2 gives an overview of the air traffic and meteorological data used in the current study. The data-driven analysis methodology is described in Section 3. Results are presented and discussed in Section 4. Section 5 summarizes and concludes the paper.

2. Data

2.1. ADS-B data
ADS-B technology traces and broadcasts the aircraft’s position and operational parameters periodically. Despite the availability of many business platforms providing ADS-B information, some of them suffer from temporal limitations. In this work, we select the OpenSky Network for its easy accessibility [6]. In particular, data pertaining to approximately 9500 flights are extracted for our study, by applying the Python package “Traffic” [7]. These data correspond to 30 days (May 1st to May 30th) of arrival flight trajectories at the Hong Kong International Airport (HKIA) and are illustrated in Figure 1 below.

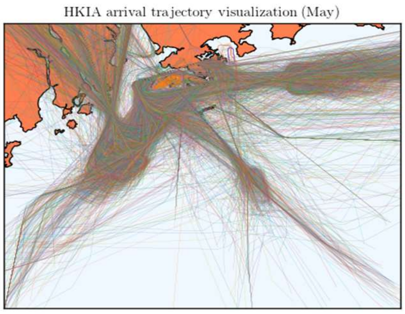

Figure 1. Arrival flight trajectory visualization at HKIA TMA.

2.2. Weather radar observations
Weather radar is a useful tool to monitor the spatial distribution and temporal evolution of convective weather around an airport. In this study, we use the weather radar images from the Hong Kong Observatory (HKO). These images are publicly available online at an observation frequency of up to once every 12 minutes and cover an approximately circular domain with a radius of 256 km around Hong Kong (Figure 2). As seen in Figure 2, the radar domain coincides well with that of the ADS-B data including the major arrival flight routes of HKIA from the east, southeast, and southwest directions. Technically, the parameter displayed is the equivalent hourly rainfall rate, but this can be directly mapped to the radar reflectivity value at a constant altitude of 3 km, which is commonly used in meteorology. While this simple planar geometry might not be an exact match of the spatially complex aircraft trajectories, we note that organized or mature thunderstorms tend to possess a 3-D structure in which radar reflectivity values can be correlated vertically in the order of several km. As such, the use of single-layer radar observations can be considered justifiable, at least as a first

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approximation. An alternative would be using the fixed elevation scans which possess a conical geometry radiating outwards from the radar location. Whether such scan data might provide a better match with the weather conditions experienced or observed on-board could be a subject of future exploration. In this paper, we focus on the one-week period of May 24th to May 30th (using the constant altitude radar data) during which the ADS-B flight records are relatively complete.

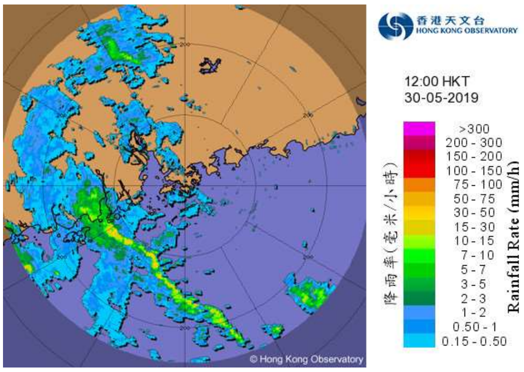


Figure 2. Weather radar image within a radius of 256 km around Hong Kong (12:00, May 30th, 2019).

3. Methodology

In this paper, we investigate the possible interaction between local weather conditions and aircraft arrival traffic by following the steps shown in Figure 3. The feature extraction of flight trajectory data is performed after completing the data pre-processing step, which will be further described in Section 3.1. The spatio-temporal relationship between weather conditions and air traffic data is then derived based on features extracted from both data sources (i.e., radar images and ADS-B data).

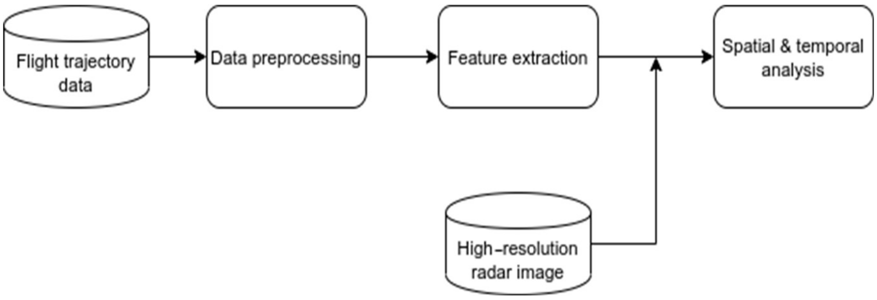


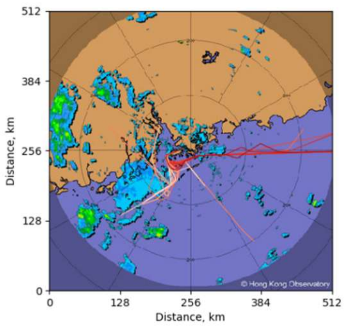
Figure 3. Step-by-step procedure to derive the spatio-temporal relationship between weather conditions and air traffic data.

3.1. Flight trajectory data pre-processing and feature extraction

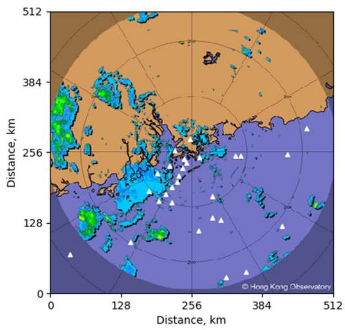
To reduce the computational cost and complexity, a trajectory simplification algorithm is introduced here to pre-process the flight trajectory data, by retaining the minimum number of points to describe a flight trajectory profile. In particular, we apply the Ramer-Douglas-Peucker (RDP) algorithm [8] for trajectory simplification purpose. This algorithm can remove redundant points along a flight trajectory. Despite this significant reduction, the algorithm still ensures the accuracy of the flight trajectory representation [1]. In this study, we focus mainly on arrival transit time and holding patterns as flights wait for their turn to land. Arrival transit time refers to the aircraft airborne time inside the TMA before landing. The presence of convective weather at sensitive locations along or around flight routes, or in close proximity to the aerodrome, can result in longer arrival transit time, causing delays and redundant fuel consumption. The arrival transit time information can be obtained from the timestamp information provided in ADS-B data. The holding pattern refers to an alternative flight trajectory in which the aircraft loiters in the air, typically in a racetrack loop pattern. In each airspace, there are pre-determined "holding areas" in accordance with local ATC procedures. By incorporating the automated holding pattern detection algorithm developed and presented in [1], arrival flights with holding patterns can easily be detected and labelled. Classifying flights with and without holding patterns can help analyze and characterize the air space utilization and air traffic delay around TMA.

3.2. Analysis of the correlations between weather radar and flight trajectory data

By matching the geo-spatial information of the radar images and flight trajectory data, these two types of data can be overlaid on top of each other to reveal the correlation between arrival air traffic congestion and the extent/intensity of thunderstorms at different locations. Figure 4a shows the superposition of the radar image and arrival transit time, which is indicated by different intensities of red color, where longer arrival transit times are represented by darker shades of red. In Figure 4b, we superpose the waypoints on the radar image, showing which waypoints are directly affected by convective weather. The resulting analyses and observations will be presented and discussed in the next section.



(a) Overlaying weather with flight trajectories colored by respective arrival transit times.



(b) Overlaying weather with waypoints.

Figure 4. Geo-spatial analysis of weather radar and flight trajectory data.

4. Results and discussions

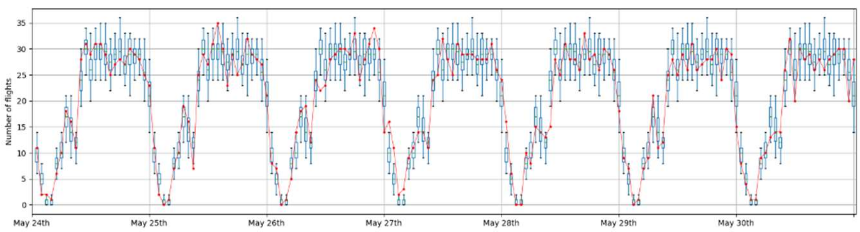
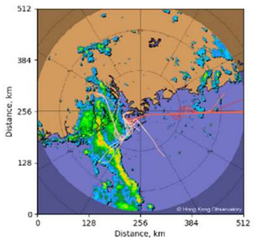


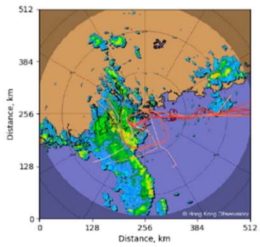
Figure 5. The hourly number of arrival flights during the 1-week study period (solid red line) as compared against the 1-month distribution from May 2019 (blue boxplots).

In this study, we use one week's flight trajectory data (May 24th to May 30th, 2019), which contain relatively complete records of all arrival flights at HKIA. The hourly variation of the number of flights within this period is illustrated by the solid red line in Figure 5. In the background, the blue boxplots represent the statistical distribution of the hourly numbers of arrival flights inside Hong Kong TMA, which are compiled from 30 days of flight information data (May 1st to May 30th) at HKIA. Figure 5 exhibits a consistent and periodical trend, due to the local flight regulations and capacity of HKIA.

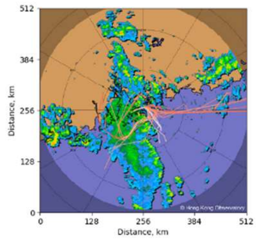
However, several periods are observed to have significantly reduced number of flights as compared to the monthly average. Based on the figure below, we select two such periods for further investigation, namely, May 26th, 09:00 -14:00, and May 28th, 09:00 - 14:00.



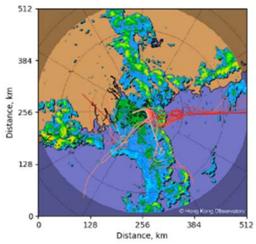
(a) 09:00



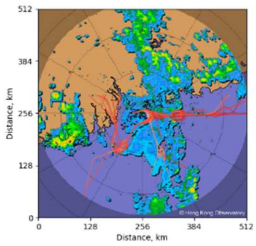
(b) 10:00



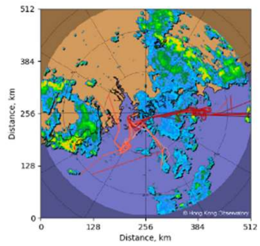
(c) 11:00



(d) 12:00



(e) 13:00

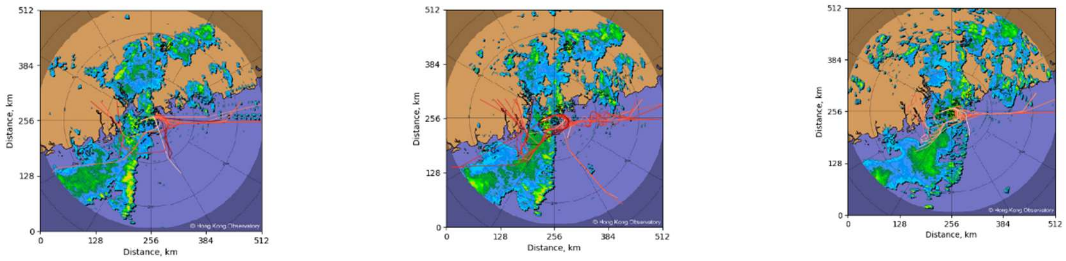


(f) 14:00

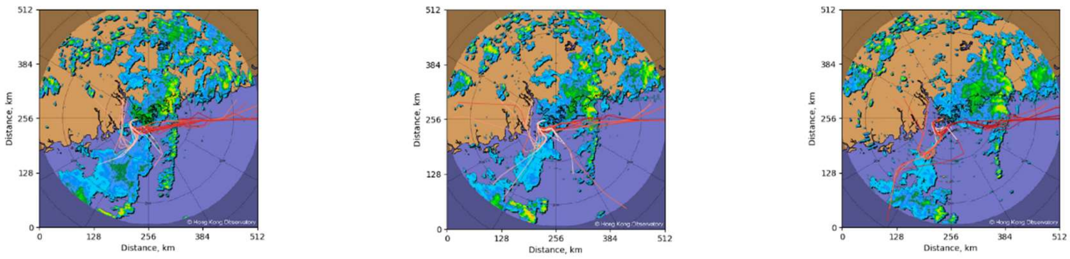
Figure 6. Flight trajectories over radar images (May 26th).

The convective weather conditions (rainfall and thunderstorm) caused a large number of delays and holdings on May 26th and May 28th. By mapping the arrival transit time over the flight trajectory and radar image, the potential reason for the abnormal arrival airborne time can be inferred. Figure 6 illustrates the aircraft arrival trajectory patterns from 09:00 to 14:00 on May 26th, while Figure 7 shows the patterns in the same time period on May 28th. Before 12:00, an extensive band of radar echoes associable with thunderstorms could be observed on both days to south-west of HKIA. Possibly due to the impending thunderstorms and changes in runway wind directions, air traffic controllers changed the landing runway from 07L/07R (west) to 25L/25R (east). Consequently, longer airborne time and numerous holding patterns were observed at 14:00 on May 26th as ATC reverted the operation back to the normal segregated mode. This observation suggests that intense thunderstorms near the terminal area can have significant impact on runway operations and aircraft arrival transit time. Moreover, a time lag is also observed between the onset of convective weather and the abnormal aircraft arrival traffic.

To demonstrate the time lag phenomenon mentioned above, first we pick a threshold for identifying convective weather, which will be a rainfall rate of 15-30 mm/h or above (corresponding to the yellow radar echoes). By counting the number of waypoints covered by convective weather for each hour (with superposition as shown in Figure 4b), we can easily observe the time lag between convective weather and arrival transit time/holding, as shown in Figure 8. In this figure, orange bars show the number of flights without holding patterns, red bars correspond to the number of flights with holding patterns, and blue bars refer to the number of waypoints covered by convective weather at each hourly time slot. From 00:00 to 05:00, since there were not many aircraft inside HKIA TMA, no significant impact of convective weather on air traffic can be observed. From 09:00 to 15:00, on the other hand, it can be seen that the number of holding patterns (and consequently higher arrival transit time) is strongly correlated to the number of waypoints covered by convective weather 1 - 2 hours earlier. This is an example of the time lag phenomenon.



(a) 09:00 **(b)** 10:00 **(c)** 11:00



(d) 12:00 **(e)** 13:00 **(f)** 14:00

Figure 7. Flight trajectories over radar images (May 28th).

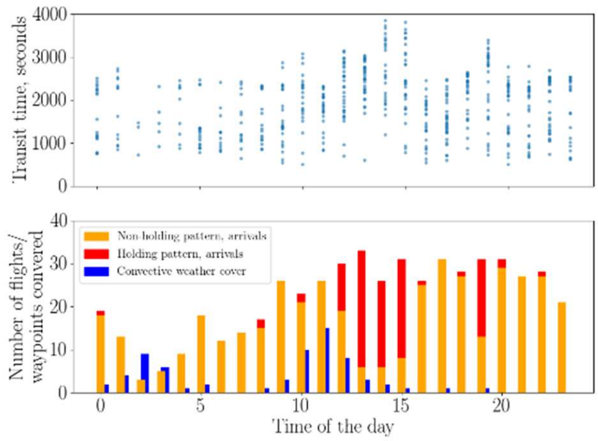


Figure 8. Hourly variations of the number of flights (holding/non-holding), number of waypoints covered by convective weather, and the corresponding transit time distribution on May 26th.

Internationally, there are a number of previous studies focusing on optimization of flight routes in relation to weather. However, these studies tend to tackle the problem from an application perspective by focusing on the construction of solutions, and hence naturally concentrate less on uncovering or extracting statistical behaviour from a "Big Data" fashion. For example, [9] applies variational methods to derive optimal trajectories at the flight planning stage by jointly considering en-route winds and turbulence distribution. At the tactical timescale, [10] simulates optimal thunderstorm avoidance manoeuvres by considering realistic ATC procedures in a "first principle" manner. This paper instead takes a data analytics approach and attempts to unveil insights on the impact and sensitivity at a major international airport. In tackling the issue of possible time lag response, we may borrow from accepted methodologies in the land transportation community [11] for a more advanced, quantitative treatment as a next step.

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5. Summary and conclusions

In this paper, the spatial and temporal relationship between convective weather and aircraft arrival performance in HKIA TMA is investigated for the first time. Results indicate that aircraft arrival traffic performance is sensitive to the spatial coverage of convective weather, with particular locations more susceptible. Furthermore, geo-spatial and statistical analysis techniques have revealed a time lag effect between weather distribution and subsequent air traffic.

Further research will continue along the following directions:

1) Extending the above analysis to a 1-year period. With more weather data, we will be able to capture the inherent seasonal and diurnal pattern for more comprehensive results.
2) Performing detailed analysis of the spatial impact of convective weather to air traffic. By using advanced geo-spatial and machine learning technology, we will derive quantitative relationship between convective weather and air traffic performance.
3) Investigating the possibility of integrating weather information within the terminal control area into air traffic models. More varieties of weather data could be explored in the next stage, such as fine-resolution numerical weather prediction (NWP) output [12].

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