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On the identification of weather avoidance routes in the terminal maneuvering area of Hong Kong International Airport

Manuela SAUER†1, Thomas HAUF[1], Ludmila SAKIEW[1], Pak Wai CHAN[2], Shuk-Mei TSE[2], Patrick HUPE[1]

(*[1]Institute of Meteorology and Climatology, Leibniz Universität Hannover, 30419 Hannover, Germany*)

(*[2]Aviation Weather Services, Hong Kong Observatory, Kowloon, Hong Kong, China*)

†E-mail: sauer@muk.uni-hannover.de

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Abstract: The safety and efficiency of air traffic are significantly affected by adverse weather. This holds especially in terminal maneuvering areas (TMA) where, in addition to the impact of weather itself, potential weather avoidance routes are strongly restricted by air traffic regulations. A weather avoidance model DIVMET has been developed which proposes a route through a field of developing thunderstorms. Air traffic control regulations have not been included in it at this stage. DIVMET was applied to the TMA of Hong Kong International Airport as air traffic control (ATC) there has become interested in improving the controller's work load, especially for managing incoming traffic by avoidance route simulations. Although visual inspection of simulated avoidance routes by ATC was satisfactory, a quantitative validation of simulated with real observed routes was also carried out. Two real adverse weather situations with thunderstorms within the TMA of Hong Kong and with heavily distorted traffic were chosen. The main objective prior to any validation, however, was to identify routes which are solely impacted by weather but do not show any signs of regulation. Route selection was done on the base of flight position data. Landing flights were selected and deviations from standard approach routes were analyzed. As a result, the majority of 272 flights were found to be affected by both weather and regulations (60%), highlighting the challenge for air traffic controllers to manage landing traffic under adverse weather conditions safely and efficiently. Only a few weather-affected flights (7%) were not regulated and could be used for validation. DIVMET simulation routes were presented to local air traffic controllers who confirmed them as potential and realistic avoidance routes. DIVMET weather avoidance route simulations within a TMA appear to be helpful but further model development has to incorporate traffic regulations, to include holdings, short-cuts, and slow-downs.

Key words: Thunderstorm avoidance, Terminal maneuvering area, Hong Kong, Horizontal circumnavigation, Collaborative decision making
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1 Introduction

Adverse weather poses a risk to air traffic safety and efficiency. In particular, thunderstorms, with turbulence, strong wind shear, downburst, hail, and icing are among the most adverse weather phenomena. International regulations, therefore, propose that pilots should avoid areas of deep convection and maintain a safe distance from storms.

In reality, the pilot decides whether or not and how to circumnavigate adverse weather. For any deviation from the planned route the pilot has to obtain clearance from the respective air traffic controller (ATCO) in charge. The proposed heading change may be confirmed or rejected. Reasons for rejections are mainly conflicts with other aircraft, closed airspaces, especially near national borders, or any other local regulations, for instance noise level mitigation. At most work places world-wide, controllers do not have access to weather information and thus do not themselves propose weather avoidance routes in cases of adverse weather.

ORCID: Manuela SAUER, http://orcod.org/0000-0002-9484-4743

That responsibility resides with the pilots, through their visual impressions of the atmospheric conditions and use of the on-board weather detection systems, such as radar. However, the achievable weather awareness by a pilot is strongly dependent on the overall atmospheric conditions. During the day and when convection occurs isolated in an otherwise clear sky, the pilot will have a good view. In contrast, at night or if the convective cells are embedded in larger scale phenomena such as fronts, they are hardly recognizable by eye. In such situations a pilot has to rely mainly on the on-board radar system. But still, even with remote sensing instruments, weather information may be incomplete as intense storms can block the radar beam and eventually hide other weather hazards behind them. Thus, pilots avoid adverse weather in accordance with their actual knowledge from instant and also past sources, including their visual impression. Because of the limited information they have, chosen weather avoidance routes may be far from optimum.

Due to limited or non-existent weather information, a controller does not know in advance what weather avoidance routes might be requested by pilots. Actually, that information might be helpful, especially in the terminal maneuvering area (TMA) in managing the sequencing of arrivals, departing traffic and also transit flights.

In an in-depth study, Rhoda and Pawlak (1999) explored pilots' behavior in the TMA of Dallas/Fort Worth in order first to understand it and then to model it. They identified a few key meteorological quantities which allow the controller in 80% of all cases and far from the airfield to decide whether a pilot will penetrate or avoid a storm. Near the destination airport the vast majority of encounters resulted in penetrations–despite the international avoidance recommendations–indicating the suppression of any lateral avoidance maneuver option. In addition, irrational correlations with penetrations were found. Arriving aircraft were more likely to penetrate a storm when they followed another aircraft or when they were late or it was dark. The authors repeated the study for en-route flight corridors and found, as in the TMA case study for the further distance from the airport, that the deviation behavior could be forecast with a false alarm rate of only 10% using a few radar-based quantities (DeLaura and Evans, 2006a). Thus, en-route and/or further away from an airport, the avoidance maneuvers are governed by weather. Close to the airport strong additional constraints influence the decision and seemingly lead the pilot to accept a higher risk and, in the worst cases, even to make storm penetrations.

Sharman *et al.* (2011) analyzed flight trajectories under clear air turbulence (CAT) conditions in order to relate adverse weather to pilots' behavior and consequently to airway capacity reduction. The latter effect was also investigated by Krozel *et al.* (2007) and weather impacted capacity was forecasted by Song *et al.* (2006; 2007). Kim *et al.* (2015) investigated an automated application for air traffic management (ATM) to mitigate the adverse CAT impact. All forecasts are based on the precise knowledge of how pilots avoid adverse weather. For that purpose the Convective Weather Avoidance Model (CWAM) was developed which translates convective weather information into an ATM impact (DeLaura and Evans, 2006b). Chan *et al.* (2007) determined the accuracy of CWAM by comparing flown trajectories with CWAM forecasted regions where avoidance maneuvers were expected. DeArmon *et al.* (2013) tried to model the avoidance routes in order to determine the expected delays caused by weather. The concept of Dynamic Weather Routing (DWR) developed at NASA Ames Research Center in the US together with ATM and other organizations was successfully implemented and tested (McNally *et al.*, 2012; 2015). Fuel and time could be saved by adjusting planned routes to the actual weather. One important issue for route optimization is the weather related uncertainty. Adequate methods to deal with uncertainty are under development (Lauderdale and Erzberger, 2013; Sauer *et al.*, 2014).

In this paper we investigate weather impacted avoidance routes in the TMA of Hong Kong International Airport (HKIA). We follow a suggestion of Rhoda and Pawlak (1999) to compare the findings of their studies from Dallas/Fort Worth with similar studies at other airports. As will be shown below, air traffic control (ATC) in the TMA of Hong Kong is faced with a specific problem that the airspace north to Hong Kong is practically closed for any avoidance maneuvers. This fact, therefore, has to be taken into account when a pilot asks for an avoidance maneuver. The degrees of freedom for ATC operations are seemingly more limited at HKIA than at other airports. In consequence, simple and generic avoidance maneuvers, as shown left in Fig. 1, followed by an otherwise unregulated flight on the planned trajectory, for instance, will be found less frequent. Instead maneuvers will be affected by regulations often exhibiting a complex pattern (further flight trajectory in Fig. 1). So the question arises, what portion of all weather-affected flights shows a generic avoidance pattern and what portion features additional signs of ATC regulations such as slow-downs, short-cuts, and holdings. Or in other words, how many flights are simply weather impacted? For that purpose we have to identify and discriminate between generic weather avoidance and regulation patterns.

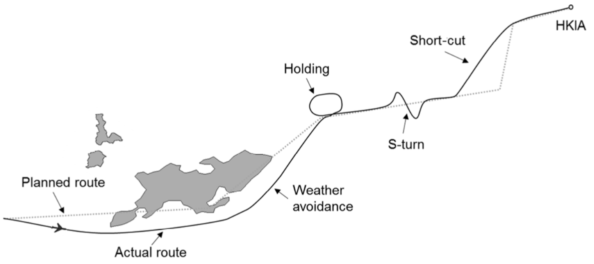


Fig. 1 Generic route with weather avoidance maneuver and regulation patterns including a holding, a slow-down (S-turn), and a short-cut on the approaching flight to HKIA

This is of relevance for the development of any kind of weather avoidance route modeling. One of such models is DIVMET (Hauf *et al.*, 2013). DIVMET simulates weather avoidance routes around or through a field of storms based on ground based radar reflectivity fields of convective cells. It assumes that in general pilots will avoid facing thunderstorms which they either can see by eye and/or in the on-board radar screen. Typically, a radar reflectivity value of about 37 dBZ will not be penetrated by a pilot and consequently will be circumnavigated. Simulated routes are as close as possible to the planned ones. DIVMET also provides information on estimated times of overfly (ETO) at certain points in space. In order to account for aircraft-specific performance data and for standard operational arrival procedures DIVMET may be coupled to the air traffic model NAVSIM, developed by Rokitansky (2005). But even in that coupled mode neither holdings nor slow-downs are so far included.

Compared with international standards, ATC and ATM in Hong Kong are very well equipped with all kinds of aviation related weather information. Controllers have easy access to instant radar weather at each work station. In order to facilitate the coordination of arrival and departure traffic under adverse weather and especially to enhance the arrival manager (AMAN), ATC is interested in avoidance route simulations. First simulation examples were given by Hauf *et al.* (2013). However, it became clear that a quantitative and detailed evaluation of simulated avoidance routes was necessary. Due to the methodological problems mentioned above, any evaluation has to be done with routes where no sign of regulation is apparent. Thus, the necessity arose to identify weather impacted routes and, among them, discriminate between those affected by regulations and those which were not. For that purpose we use flight position data which were kindly provided by the Hong Kong Aviation Services and the Hong Kong Observatory. Two days were selected with strong convective activity and where air traffic was affected by the latter.

This paper is structured as follows. First, the DIVMET model is explained in Section 2. Section 3 provides information on HKIA and the structure of its TMA. The evaluation is based on two cases; the weather situation of each is explained in Section 4. The main focus of this paper is found in Section 5 with the flight data analysis. As an application of the trajectory analysis we perform route simulations with DIVMET and compare planned routes with actually flown ones. The methodology of this model evaluation is illustrated, and results are presented in Section 6. Summary and conclusions follow in Section 7.

2 DIVMET—the adverse weather avoidance model

To understand the interaction of the complex systems of air traffic and adverse weather, the weather avoidance model DIVMET was developed by Hauf *et al*. (2013). DIVMET proposes a realistic route through a field of developing convective cells.

It simulates the decision making process of a pilot which is mostly based on the on-board radar, supplemented by visual observations.

2.1 Weather in DIVMET

Adverse weather airspaces, such as thunderstorms or icing regions as well as volcanic ash clouds, are considered as contiguous spaces with contours that can be approximated by 2D polygons. In this study thunderstorms are considered as being comprised of individual storms or convective cells. The polygons are referred to as weather objects, which are extracted from radar image data by using certain reflectivity thresholds (mostly radar levels around 37 dBZ, here 36.5 dBZ). Full radar scans are provided as images every 6 min which allows monitoring the growth and decay of storm cells. Each weather object has to be circumnavigated and can be considered as a "no-go zone" being significant for hazard avoidance. Information about its vertical extent is very often not yet provided by radar products.

Thus, DIVMET operates on horizontal planes, usually at flight levels. Due to the missing vertical storm extent and for the sake of simplicity, a cloud in DIVMET is assumed to range from surface level up to the tropopause at about 12 km height. The overflight of storm cells, especially growing lower ones, is not considered. This assumption is supported by observed pilot behavior where a horizontal circumnavigation of a storm cell is preferred to an overflight.

2.2 Safety distances kept by DIVMET

In compliance with international regulations proposing maintenance of certain distances from storms, DIVMET enlarges every weather object by a given safety distance. This emerged polygon is then enclosed by a convex hull, and further referred to as a risk area. Safety recommendations are not uniform. NATS (2010) requires safety margins of 10 NM (1 NM=1852 m) to 20 NM from any thunderstorm depending on the flight level; FAA (2010) gives distances depending on the severity of the thunderstorm. Severe thunderstorms should be avoided by at least 20 NM. If radar echoes of neighboring cells are separated by at least 40 NM, passage through the gap is allowed. A circumnavigation of the entire area becomes necessary in case of thunderstorm area coverage of 6/10 (FAA, 1983).

The safety margin, therefore, ranges between 10 NM and 20 NM. Observations, however, show a whole range of distances kept from storm cells, especially in a TMA where pilots flew inside the recommended safety distances. Distances kept by individual pilots, therefore, follow a distribution rather than a step function (DeLaura and Evans, 2006a). Safety distances kept are strongly related to freight (passengers or cargo) on board (Rhoda and Pawlak, 1999), to human factors such as personality and different risk acceptance, which themselves depend on the pilot's familiarity with the region. While cargo airliners often ignore convective cells, private business jets seem to be very cautious and can be willing to make larger detours than a commercial airliner (Thales Avionics, 2010). As will be seen later on in this paper, pilots in the TMA of HKIA took about 2 NM to 3 NM in the analyzed weather situations in May 2011. For simplicity we assume a rigid, but from case to case variable safety distance. Thus, our approach differs from the one of DeLaura and Evans (2006a), as we have not developed "weather avoidance fields" so far. In reality, a safety distance distribution is observed. The choice of a fixed radar reflectivity threshold for defining a weather object has to be seen in context with the aforementioned simplification of a constant safety distance. Both assumptions will be replaced in a later version of DIVMET by a distance distribution based on observed pilot behavior and radar reflectivity fields. For the time being, however, the focus lies on the deviation methodology rather than on the sensitivity to both the above assumptions although the resulting routes will vary in shape and length if one or the other parameter is changed. A noteworthy effect of increasing safety distance is the clustering effect of neighboring objects.

2.3 DIVMET's calculation procedure for a deviation route

In this study we assume that the pilot has a complete knowledge of all storms in the area. DIVMET allows also for avoidance route simulations with only a limited knowledge of the weather situation, the spatial dimensions of which are typically given by the on-board weather radar range.

In any case where the planned trajectory overlaps with any of the known risk areas, the determination of a deviation route is initiated. The trajectory consists of at least two points (A and B) in space that are linked by a straight connection on the great circle. A decision has to be made whether to circumnavigate the adverse weather to the left or right. It is reasonable to base this decision on the spatial extent of visible and known risk areas left and right of the planned trajectory. If the weather objects occupy more airspace to the left, the real aircraft as well as the simulated one will deviate to the right, and vice versa (Fig. 2).

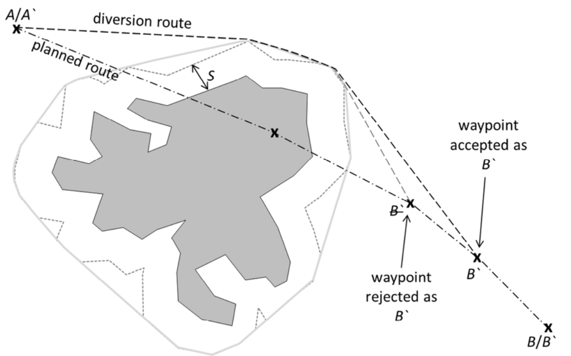


Fig. 2 DIVMET concept for avoiding a weather object (gray). The latter is surrounded by a safety margin at a minimum distance *S* (dotted line). The corresponding convex hull (solid line) is referred to as risk area. As its extent right of the planned route is larger, the aircraft would deviate to the left starting from waypoint (*x*) *A*. The deviation route to the potential rejoin route point closest to the risk area is rejected as the heading change would exceed 30° at *B*`

Air traffic in its current state follows well defined waypoints. A requested deviation from the declared route needs clearance from the ATCO in charge. Naturally and especially in a TMA, pilots will keep the deviation short and tend to follow their route as long as possible. Often an aircraft rejoins the planned route if the conflict is cleared. Thus, available waypoints in front of and behind the conflicting risk area region are determined and considered as potential leave (A`'s) and rejoin ($B$`'s) route points, respectively. Starting with the points next to the conflict region, a deviation route is determined as described below. Necessary heading changes to leave and rejoin the declared route are monitored for staying in certain ranges. A heading change should not exceed 30° as this is a common turn. If this limit is exceeded, the respective previous (A`) or next ($B$`) point is taken and the procedure is repeated (Fig. 2).

The deviation route between A` and $B$` leading around and between storm cells is based on a conventional convex hull approach. Each risk area is deviated on a trajectory that basically consists of three parts: a tangent from point A` to the risk area, a section of the convex hull and a second tangent leading from the risk area's convex hull to point $B$`. In case of more than one weather object, the deviation route can also lead through the gap between two objects. From geometrical considerations the deviation route is preferably short but it is not necessarily the shortest path possible.

For simplicity, a generic aircraft is assumed rather than treating each aircraft independently and according to its flight performance. Furthermore, a constant speed above ground is assumed in this study. If aircraft performance and a varying speed are relevant for the problem under consideration, DIVMET can be coupled to an air traffic model like NAVSIM (Rokitansky, 2005; Rokitansky *et al*., 2007), which can simulate those features.

2.4 Special cases and conditions in DIVMET

While the aircraft moves, a weather update may occur. As the weather also moves or because new cells are appearing it might happen that the aircraft is suddenly within a risk area. Similarly an airport may be covered suddenly by a storm. Two cases have to be considered. Either the aircraft is within the weather object or it is flying inside a given safety distance. In the latter case the safety distance is reduced iteratively until the aircraft is outside the reduced risk area. When being within a storm area, international regulations by NATS (2010) state that the original heading should be maintained as it is usually the quickest way out of the area. This means, when the aircraft is within a weather object the associated risk area is ignored by DIVMET to allow the flight to continue. Both effects result from discontinuous weather updates. In reality, a pilot will adjust his route continuously in response to an approaching or developing storm.

2.5 DIVMET's output

DIVMET allows for different kinds of applications that are already published elsewhere in parts.

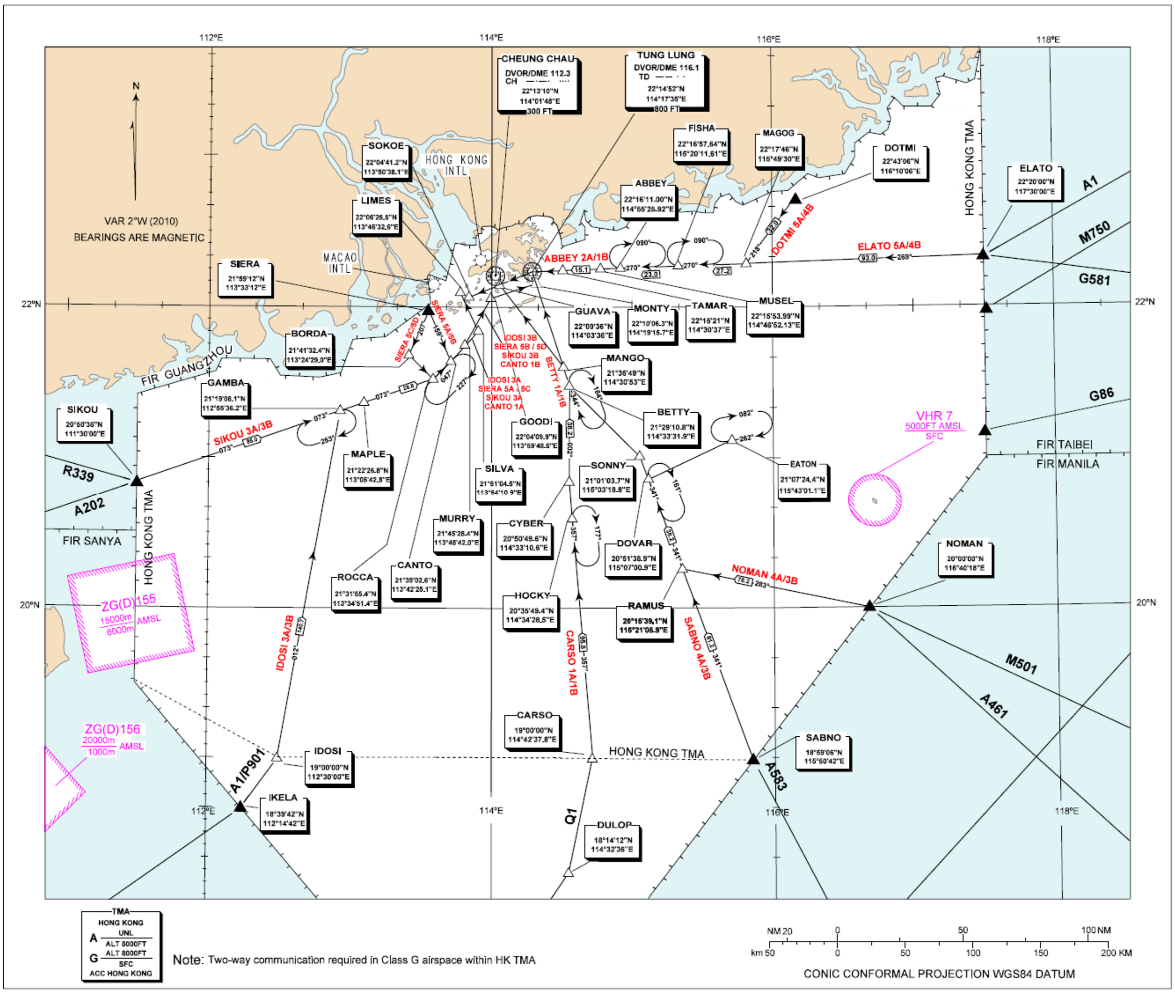
The basic output is a visualization of the planned and suggested weather avoidance trajectory together with the actual weather situation. When animating the visualization, the virtual aircraft moves with a constant velocity on the suggested route. The latter becomes updated if new weather data is available. The additional flown distance is the main output from which ETO, delay, and extra fuel are derived. Further quantities of interest may be calculated. By coupling DIVMET to the traffic simulation tool NAVSIM that accounts, e.g., for aircraft performance, more accurate and sophisticated output data can be gained (Hauf *et al.*, 2013).

3 TMA of Hong Kong International Airport

HKIA is one of the busiest airports in the world. For passenger traffic, Airport Council International ranks it at number 10 with more than 53 million passengers in 2011 (Airport Council International, 2012). In terms of freight, HKIA topped the list in the last three years (2010–2012) with above 4 million tons (Hong Kong International Airport, 2013) after having been the number two behind Memphis since the year 2000 (Airport Council International, 2012). HKIA is connected to about 180 destinations and, due to its location in Southeast Asia, serves as a multi-modal hub of international connections–especially to Oceania. On a two-runway system in parallel southwest to northeast (07/25, for runway orientation in 70°/250°) configuration and a declared capacity of a maximum 68 flights per hour (usually in practice 33 arrivals and 33 departures) about 1000 flights depart and land each day (Hong Kong International Airport, 2013). Air traffic in the airspace is organized on routes that connect waypoints in a straight way. The waypoints serve as orientation points in space. A network of routes is published by each Air Navigation Service Provider. Especially because of nearby airports, TMA airspace is highly congested and a clearly defined structure is necessary to separate the three modes of departing, arriving and transitioning traffic safely. Therefore, routes for each mode as well as, e.g., locations of holding patterns for arriving traffic are published and should be followed whenever possible. The dependency between routes and between the availability of routes and airport capacity is strong. For instance, in case of closely parallel directed arrival and departure routes, the latter need to be blocked whenever aircraft on the arrival route might need to deviate in their direction (e.g., because of adverse weather) as the minimum aircraft separation would no longer be ensured. If a departure route is unavailable, the airport capacity automatically drops and the throughput of arrivals and departures decreases. Consequently aircraft have to be delayed on ground or airborne in a holding pattern. Thus, a deviation of one or a small number of directly affected (by adverse weather) flights that may only be lightly delayed themselves because of their respective maneuvers might disturb the traffic system, triggering a delay that propagates through the system and affects a large number of flights which are not directly affected by the present weather situation.

A chart of runway independent arrival routes and terminal holding patterns in the Hong Kong TMA is shown in Fig. 3. The TMA ranges in southward direction over the sea and is bounded by the 3 NM off-shore shifted coastline of Mainland China. HKIA is located in the northern center of the TMA. Three other airports Macao, Shenzhen, and Zhuhai are located within 65 km distance in western, west-southwestern, and northern directions from HKIA, respectively. Guangzhou is located 140 km northwest of HKIA. Because of the congestion of airspaces in the vicinity, an approach to HKIA is designated from eastern, western, and southern directions rather than from the north. Eight arrival routes that lead to the Standard Terminal Arrival Routes (STAR) SIERA (west), BETTY (south), and ABBEY (east) can be identified from this chart and are flown depending on the aircraft's origin and the overall traffic situation. These routes do not lead directly to a runway. A transition to a final approach path dependent on the current runway configuration is necessary at waypoints LIMES or TD 17 NM in direction 343° (north-northwest) of Tung Lung in an altitude of about 9000 ft (1 ft=304.8 mm). The approach paths take into account the specific needs for supporting instruments for landing and are stated in a so-called Instrument Approach Chart for each runway (e.g., 25L) included in the respective Aeronautical Information Publication (Civil Aviation Department Hong Kong, 2011).

AREA CHART   ARRIVAL ROUTES AND TERMINAL HOLDING PATTERNS



Note: Two-way communication required in Class G airspace within HK TMA

Civil Aviation Department Hong Kong

Fig. 3 Arrival routes and terminal holding patterns in the Hong Kong TMA as stated in the local Aeronautical Information Publication (Civil Aviation Department Hong Kong, 2011)

4 Weather situation on May 22 and 23, 2011

The traffic response to two consecutive adverse weather situations on May 22 and 23, 2011 in the Hong Kong TMA is investigated. The Hong Kong CAPPI (constant altitude plan position indicator) product serves as weather input. A representative rainfall rate distribution picture of each situation is given in Figs. 4a and 4b. The radar device, located on the highest peak of Hong Kong, Tai Mo Shan at an altitude of 968 m above mean sea level (in the center of the image), has a maximum range of 256 km (lighted circle) and provides volume scans of the atmosphere from which data for the CAPPI product at 3 km is calculated. The radar echo is marked by a color scale. Yellow pixels indicate strong echoes of more than 15 mm/h. As stated above, 36.5 dBZ (7.5 mm/h) indicate critical conditions regarding convection and other related dangerous phenomena and, thus, are often avoided by pilots. Reflectivity values around this threshold (starting at 7.5 mm/h that equals 36.5 dBZ) are shown in light green. Pixels of this and warmer colors are extracted and translated into polygons for weather conflict detection.

In the morning of May 22, 2011 Hong Kong came under the influence of a low pressure system located over the northern part of the South China Sea. During the morning the active pressure trough with heavy rainfall and embedded thunderstorms travelled northeastwards over the TMA of HKIA. One snapshot of the situation at 13:42 HKT (Hong Kong Time, 05:42 UTC) is shown in Fig. 4a.

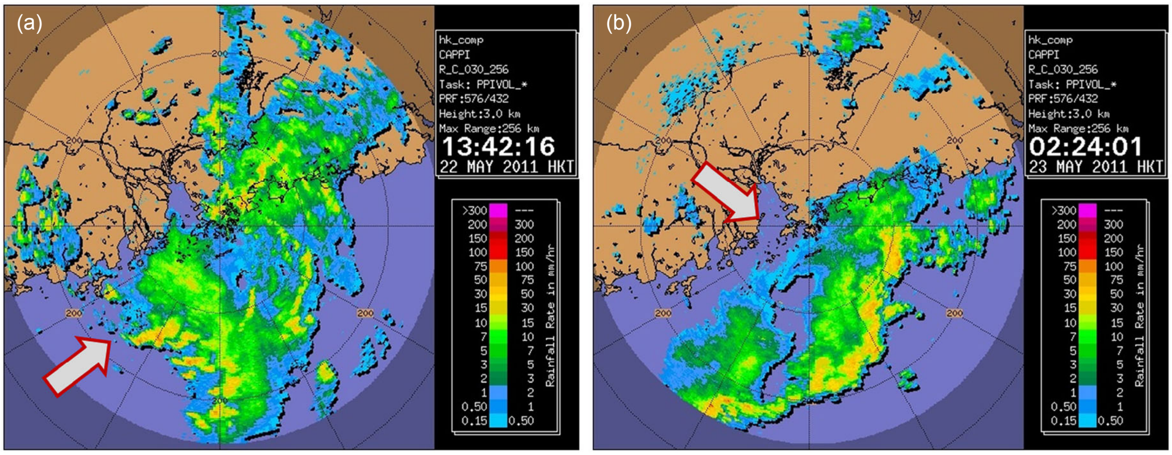


Fig. 4 The Hong Kong radar composite shows the rainfall rate field on a color scale. Light green to yellow areas indicate strong echoes caused by large raindrops or ice particles marking the areas of deep convection and heavy rainfall

(a) Around midday (HKT, UTC +8 h) on May 22, 2011, a stretched precipitation area travelled northeastwards across the radar range of sight; (b) During the next night (HKT, UTC +8 h) on May 22 to 23, 2011 another more smoothly structured precipitation area travelled southeastwards through the radar field of sight

Note: for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article

In the evening of the same day another trough of low pressure over inland Guangdong tracked southwards to cross the coast. The associated strong precipitation cells are arranged more smoothly in a line in this situation, as can be seen in Fig. 4b for 02:24 HKT. Altogether, the weather situation on May 22, 2011 brought more than 100 mm of rain in wide parts of Hong Kong and even more over the New Territories (Hong Kong Observatory, 2011).

Floods and landslips were reported and air traffic in Hong Kong TMA was impacted as well. Standard arrival routes as described in Section 3 were blocked and deviations from these routes became necessary. As a result detours and delays came about that are analyzed based on traffic data provided by the Hong Kong Observatory.

5 Flight data analysis

5.1 Flight trajectory identification

Flight data for both cases was given as a set of *n*-tuples comprising time, latitude, longitude, aircraft identifier, altitude, and other parameters not considered in this study. Out of more than 1.2 million data tuples suitable tracks of 524 aircraft in the morning (case 1, 07:00 HKT to 15:00 HKT) and 545 aircraft during the evening and night (case 2, 18:00 HKT to 03:00 HKT) were distilled with radar based support points separated by 5 s.

Aircraft trajectories were processed, first, to distinguish traffic from and to HKIA, to other airports and overflights. In the end, 133 and 139 approaches to HKIA were identified during the day and in the evening and night of May 22 and 23, 2011, respectively.

The eight inbound routes merge into the three STARs SIERA, BETTY, and ABBEY, which are utilized by flights of the data set at 34%, 18%, and 48%, respectively, which is more or less in line with the overall traffic pattern in the Hong Kong TMA. Almost all identified cases, in which an aircraft originating from one direction switches to another STAR that approaches the airport from another direction, occur from east or west to the southern STAR which shows less traffic density than other routes.

5.2 Trajectory characteristics

All 272 inbound trajectories to HKIA were inspected visually and attributed to various categories as listed in Table 1 and as explained in the following. Routes without regulation do not show any effect of regulation procedures such as holding, slow-down, short-cut or switch of STAR. Note that each trajectory may have more than one attribute. For example, a flight might be slowed down and switched to another STAR. Visual inspection also allows attributing for many, but not all, flights a STAR and, thus, the original planned route. If now this planned route encounters a weather object it is referred to as being affected. Cases where cells are deviated are also listed, as well as when a cell is encountered in or after a deviation process.

As listed in Table 1, 16 and 25 approaches for the first and second cases, respectively, were obviously not regulated significantly by ATC. All other flights show at least one of the characteristic regulation patterns. These are short-cuts, also called directs, for example the one shown in the northwest corner of Fig. 5b. ATC also regulates by slow-downs and holdings to retard a flight by about 2 to 4 min and 5 to 6 min, respectively. Slow-downs are visually recognizable by so called S-turns, also shown in Fig. 5b south of the printed name BETTY. Holdings are round or oval-shaped patterns in certain airspaces. Examples of holding flights are given in Figs. 5a, 6a, and 6c. Some other trajectories show a switch of the STAR, which may be imposed by ATC because of blocked (either by weather or traffic) holding areas in the formerly assigned STAR (Fig. 5a). This mostly occurs on the frequently utilized eastern and western inbound routes. Hence, in those cases and in line with the above mentioned general trend, traffic is mostly shifted from these STARs to the southern inbound routes approaching HKIA via BETTY.

Altogether 184 of 272 routes (68%) were affected by convective cells exceeding 36.5 dBZ. 125 (=61+64) of these flights deviated from their originally assigned STAR. Nevertheless, 64 of the deviated flights experienced a cell encounter. Another 59 (=184−125) seemingly ignored the adverse weather and encountered at least one cell. A weather object was encountered by 67% of all affected aircraft (45% of all arrivals). In seven non-regulated flights weather was avoided.

In many other cases it can be observed that pilots tried to avoid higher intensities and use gaps or pass between two intensity peaks. Thus, the actual avoidance maneuvers may be more than that are listed.

Individual pilot behavior can be identified. Some pilots choose longer detours and fly holdings outside the actual holding area to avoid the weather by a larger margin (Fig. 6a). Other pilots do not avoid all cells, usually slightly less intense ones than in the case described before. Some even fly holdings within adverse weather as shown in Fig. 6c. A missed approach can be identified here as well. They often occurred during times of wind-induced runway configuration changes.

Note that the number of cell encounters might be misleading. One reason is the absence of information on the weather object's vertical extent. The CAPPI radar product gives information for the 3 km altitude level. An inbound flight's descent crosses all flight levels and altitudes between about FL330 and ground level and, thus, may actually fly above or beyond the indicated cells. However, international regulations advise pilots against overflying deep convection because of strong turbulence above the visible cloud. In cases of weak convection 5000 ft vertical separation should be maintained (NATS, 2010).

A statement concerning delays of flights is not possible due to the lack of information on planned times.

For validation purposes of DIVMET and in order to rate the model's capability for an application in the TMA of an airport, the aim is now to check whether DIVMET is able to represent the observed flight characteristics of directly affected aircraft.

Table 1 Traffic numbers, regulation patterns, and weather impacts for the two cases

Case	Arrivals*	Non-regulated	Regulated	Regulation patterns				Weather-affected routes**	Diversion routes, no cell encounter	Diversion routes, cell encounter(s)
				Holding	Slow-down	Short-cut	Switch of STAR			
1	133	–	117	63	60	30	12	76	26	20
		16	–	–	–	–	–	4	1	3
2	139	–	114	55	33	30	18	88	28	31
		25	–	–	–	–	–	16	6	10
Total	272	41	231	118	93	60	30	184	61	64

* Arrivals are divided into regulated and non-regulated flights. Each regulated flight exhibits at least one regulation pattern. ** Weather-affected flights without any deviation maneuver can be gained by subtracting deviated flights from affected routes

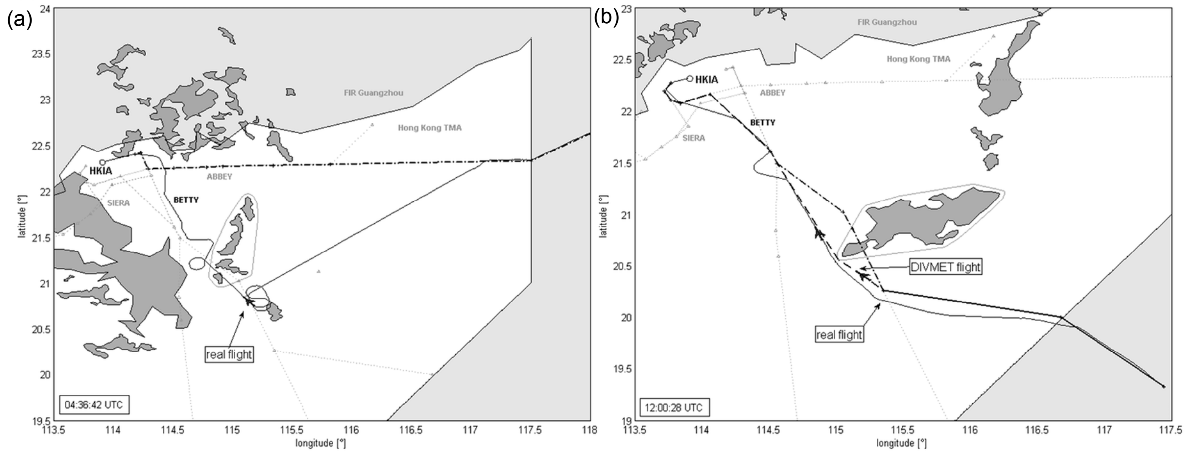


Fig. 5 (a) Weather objects (reflectivity>36.5 dBZ=7 mm/h, dark gray areas) in and outside the TMA of Hong Kong (white area); central weather object enclosed by a 2 NM safety margin (thin gray line); STARs in thin dotted gray lines with waypoints (triangles and crosses); example of a real flight (solid black line) that switched from an eastern planned route (dashed-dotted line) to the southern STAR (BETTY) with two holding patterns. (b) Example of a flight from southeast with the planned route crossing a weather object; southwest deviated real flight with a slow-down and a following short-cut regulation pattern further northwest. Additionally, a DIVMET simulation flight is plotted, superimposed to the planned route, but deviating from the latter near the weather object (dashed line)

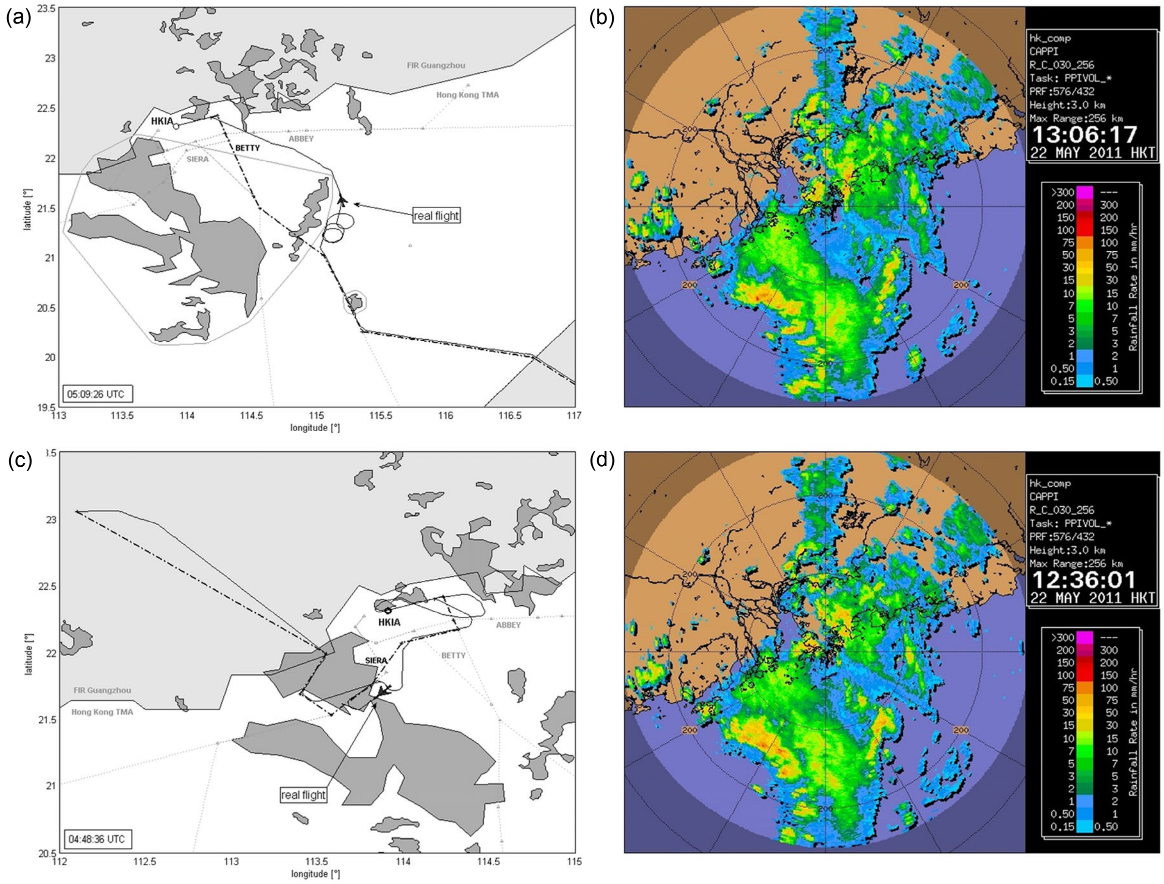


Fig. 6 Aircraft trajectories including holding patterns; line coding in plates (a) and (c) as shown in Fig. 5. (a) A flight at 05:09 UTC (13:09 HKT) deviating from its planned route with holdings, N.B. outside the actual holding area, and avoiding the weather objects in the northwestern area, appearing in the radar rain rate picture (plate b) as the yellow line structure (>15 mm/h) in the southeastern sector; (c) Same day, about 30 min earlier: flight from northwest through a cell (about 7–10 mm/h) with holdings in the same cell but within the actual holding area

Note: for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article

6 Evaluation of DIVMET—methodology and results

For validation of DIVMET we choose a qualitative comparison of simulated and observed directly affected, non-regulated inbound routes to HKIA. Thus, the approach is similar to that in Hauf *et al.* (2013), except that we have now distinguished regulated from non-regulated flights. The available sets of aircraft trajectories were analyzed as described above. Non-regulated flights that were neither put on holdings to gain a delay nor otherwise delayed nor accelerated significantly are taken as reference data for these simulations. The remaining flight time of inbound traffic within the Hong Kong TMA ranges between 15 min for flights coming from the north to about 1 h especially for those from the southern and eastern directions.

Apart from the reference flight of the data set, a virtual flight is released at the same time and position as for the real flight. The planned trajectory of the virtual flight is given by the inbound route and associated STAR which the real flight has probably taken. The mean flight velocity of the latter (except for the last 150 s before landing) defines the constant speed of the virtual flight. This leads to different positions of both aircraft in all following figures where the real aircraft heads ahead of the DIVMET flight, which itself outruns the real one when approaching the airport, as the latter decelerates then.

Depending on the situation, there may be only a few cells or, if the whole area is filled with small cells, they will merge when applying a large safety distance. The safety distance is varied between 0.1 to 2.0 NM in the simulations.

When simulating the virtual flight and determining a deviation route in conflict cases, the planned trajectory is tracked as long as possible and is rejoined at the next waypoint as soon as the flight clears the conflicting region while allowing for the angular criterion of 30° described in Section 2.4.

For validation purposes the simulated route of the virtual DIVMET flight and the reference trajectory are visually compared in a qualitative way and presented to local air traffic control staff. Only seven flights were identified where the actual flight has not been regulated at all and the pilot followed the STAR precisely but avoided adverse weather (Table 1).

Example 1. A flight with good agreement between simulation and observation is given in Fig. 7.

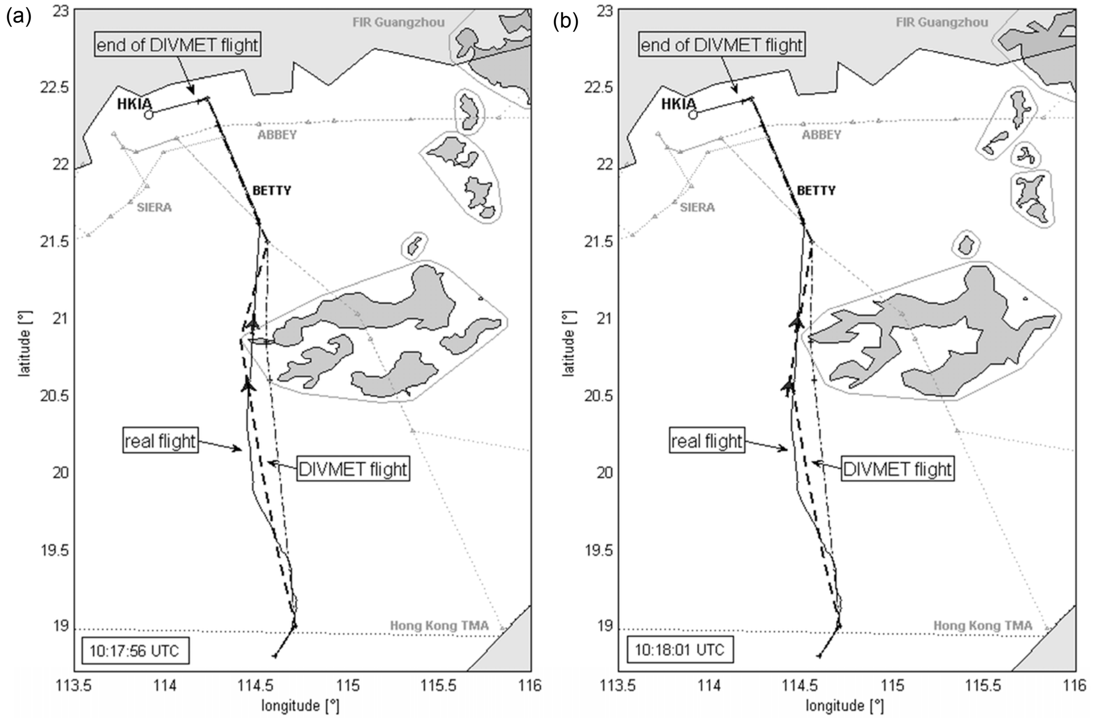


Fig. 7 Comparison of a DIVMET simulated flight (bold dashed line) with an observed trajectory (solid line) that apparently has not been regulated by ATC. Line coding as in Fig. 5

(a) Weather situation at 10:12 UTC with aircraft positions at 10:17:56 UTC; (b) Aircraft positions and updated weather information at 10:18:01 UTC

The left panel (Fig. 7a) shows the weather situation at 10:12 UTC on May 22, 2011 with the aircraft position at 10:17:56 UTC, nearly 6 min later. The reference trajectory is given by a solid line; the deviation route simulated by DIVMET is shown as a bold dashed line. The planned inbound route on which the deviation route calculation was based is given dashed-dotted. Other inbound routes and STARs are given in gray. Triangles and crosses indicate waypoints; those on the planned trajectory serve as potential leave and rejoin route points.

Both aircraft deviated from the inbound route and circumnavigated the weather on the left hand side. In the simulation a safety margin of 2 NM is assumed (gray solid line enveloping the four weather objects). The real flight, however, seems to have just passed the small edge of the western weather object. This is an effect of discrete weather information updates at every 6 min. In this case the most recent update was nearly 6 min old. The next weather update (Fig. 7b) reveals a shrinking adverse weather field and its eastward shift. It is very likely, therefore, that the aircraft did not actually enter the adverse weather but passed close to it. Because of the refreshed weather information the DIVMET simulated flight in Fig. 7b changes its heading earlier towards the rejoin route point on the planned STAR. In the end, the simulated flight is, at 2.87 NM, slightly longer than the real one.

Example 2. Another comparison between a DIVMET flight and a reference trajectory of the same day at 10:37 UTC is presented in Fig. 8. The real flight took a much longer detour around the weather field. Further north it also deviated to the north of the STAR. This might be related to the change of the runway configuration at HKIA which was switched from eastern to western approaches at 11:00 UTC. The real flight finally landed at 11:03 UTC, having flown a detour of 18.9 NM compared with the DIVMET flight.

Example 3. The flight shown in Fig. 9 was only slightly affected. The simulated flight follows exactly the STAR, while the real one deviates from the planned route, thus creating a 15 NM longer approach which could also be on purpose to delay the flight.

The four other flights of the non-regulated ones show simulated routes that were almost 11 NM shorter on average than the respective reference trajectory. In some cases the latter showed detours, similar to Example 3, lacking an obvious explanation.

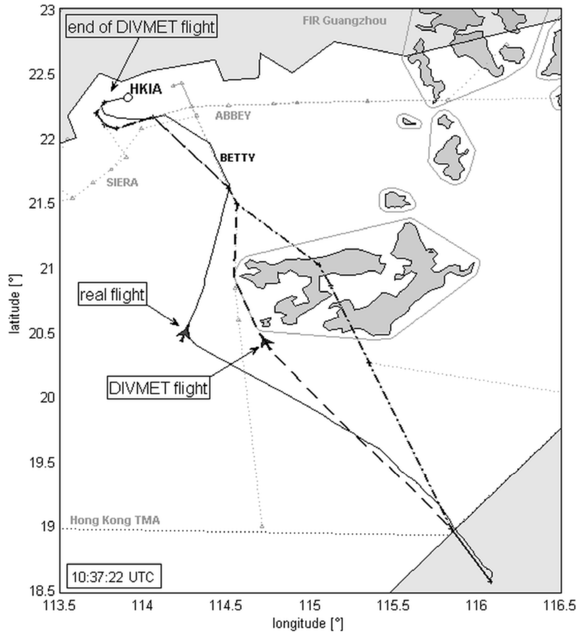


Fig. 8 Simulated and observed flights at about 10:37 UTC on May 22, 2011. Line coding as in Fig. 5

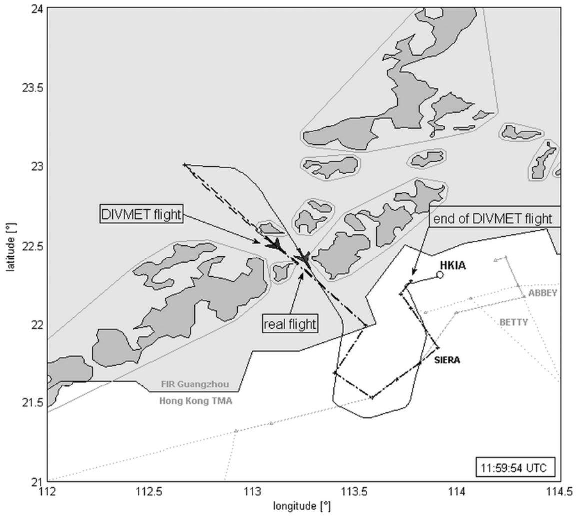


Fig. 9 Simulated and observed flights at about 12:00 UTC on May 22, 2011. Reduced safety margin of 0.1 NM. Line coding as in Fig. 5

Another 13 trajectories were affected only by weather and deviated but still encountered a weather object (not shown). In addition, regulated flights have been compared with DIVMET flights, only illustrating the differences between regulated flights and simulated unregulated but weather-affected flights (not shown).

7 Conclusions

Approaching traffic under adverse weather conditions in the Hong Kong TMA has been investigated. For two periods of 7 h length each, on May 22 and 23, 2011, 133 and 139 approaching aircraft trajectories were identified. Each trajectory was inspected by eye and was assigned various attributes. Those were: regulated flights (231), weather-affected flights (184), flights unaffected by either weather or regulations (21, see Table 1). As regulation patterns, slow-downs, holdings, short-cuts, and switches of STARs were found. Only 15% of all flights approached the airport without any visually recognizable regulation by ATC.

68% of all flights were affected by adverse weather but only 125 of these 184 flights deviated from the assigned STAR. Sixty-four of these deviated flights, plus 59 aircraft that did not try to avoid the conflicting cells at all, encountered at least one convective cell. Results were presented to Hong Kong ATC staff.

Suitable for validation purposes are those flights which successfully deviated due to the weather situation while not being regulated by ATC. Seven reference trajectories were found in the data set. This seemingly small number indicates that weather is seldom the only factor impacting the approaching traffic. However, it does not imply that weather is unimportant, as in 164 cases flights were affected by both weather and regulations. The latter emerge not only from the general sequencing problem but also from the special geographical situation of the Hong Kong TMA where the airspace to the north is restricted by the border to mainland China. This makes the TMA of Hong Kong exceptionally challenging, especially under adverse weather situations. In addition to the regular traffic coordination the weather situation needs to be intensively monitored by the controller, which leads to a high work load in adverse weather situations. Procedures to compensate for blockages of arrival routes either because of adverse weather or due to high traffic density are on hand. Controllers in the Civil Aviation Department in Hong Kong have access to several weather products to manage those situations safely and efficiently, including nowcasts of the convective situation, that also give forecasts on blockages of single waypoints (Li, 2009).

Even when regulated, flight patterns vary a lot from flight to flight. This characteristic reflects individual pilot behavior. The phenomenon is also known from weather avoidance routes in the US (Rhoda and Pawlak, 1999; DeLaura and Evans, 2006a).

The DIVMET evaluation based on the comparison of the seven solely weather-affected flights shows good results as was confirmed by local ATC. Quantitatively, distances between real and simulated flights range within several nautical miles. In view of the aforementioned observed scatter of individual deviation flights, simulated flights can in principle not be distinguished from real ones. Or in other words, DIVMET provides realistic deviation routes. The provision of realistic routes is the optimum which under these circumstances can be achieved by simulations. Regulated flights require the implementation of such regulations, including local rules and priorities, which, however, are beyond the scope of DIVMET. This, however, can be done by an air traffic model such as NAVSIM.

An operational application of DIVMET might facilitate the mutual understanding of pilot and ATCO in adverse weather situations. By simulating each approaching flight in its respective environmental conditions and with respect to the information the pilot on board has (limited or unlimited view), the controller in charge gets an impression of how the pilot might react to the weather ahead and which requests may come in. One general objective would be to increase the predictability of traffic flow. Full view simulations could give an even better impression and might indicate more efficient routes that could be suggested to the pilot. In addition to indicating a possible deviation route, DIVMET can give a forecast of when the aircraft will reach certain points in space. The ETO then tells the controller when he can integrate the flight into the arrival manager (AMAN) sequence and whether he needs to accelerate or retard the flight. Whenever an aircraft approaches the TMA of HKIA, the controller in charge may simulate the flight according to the respective STAR and the weather situation during the further flight. To do so, information on the weather development would be necessary and it could be gained from the nowcast system SWIRLS (Short-range Warning of Intense Rainstorms in Localized Systems). The system has been developed at the

Hong Kong Observatory and provides virtual radar reflectivity nowcast and forecast information up to 6 h in advance with a time resolution of 6 min (Li, 2009; Yeung, 2012). The data can be used in the same way as radar observations and the flight trajectory can be adjusted in reaction to the next situation until the Initial Approach Fix is reached. The latter is the point where the initial approach segment of an instrument approach begins. For such an application DIVMET can be seen as a supporting tool. Although it does not provide a complete solution including all necessary regulations it deals with the effect of weather.

Further progress can be made if a traffic model is used where all the regulations are implemented. The coupling of DIVMET to the global air traffic simulation model NAVSIM (Rokitansky, 2005; Rokitansky *et al.*, 2007) has already been done and successfully tested for scenarios with up to 1800 flights within a couple of hours (Hupe *et al.*, 2014). The resulting weather avoidance routes comply with individual aircraft performance based on the EUROCONTROL Base of Aircraft Data, TMA specific flight rules, and weather.

The evaluation of DIVMET within the Hong Kong TMA was successful. The number of trajectories in such a highly regulated environment which are solely impacted by weather is small. Weather is one of many factors to be considered within the TMA by ATC to guarantee safe and efficient air traffic. DIVMET combined with NAVSIM might help to facilitate that objective. Route forecasts with estimated overflight times at specific waypoints, for instance in support of an AMAN (Erzberger *et al.*, 2010), would definitely be beneficial for ATC. A study investigating this important issue is underway.

This paper has investigated the disturbing effect of convection on the air traffic near a larger airport. In the Unites States convection is the major source of delays impacting not only the landing and departing traffic but also, and often to a larger extent, the en-route traffic when airways and larger airspaces become blocked by storms (Krozel *et al.*, 2007). Another adverse en-route phenomenon is CAT. Kim *et al.* (2015) have developed a warning and prediction system for turbulence to support ATCO. Though convection and CAT differ in vertical and horizontal scale, the methodology pursued in that work is of interest for the development of a future convection avoiding and managing tool for the Hong Kong TMA.

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中文概要

题　目：论香港国际机场起飞着陆滑行区域气象回避路线的识别

概　要：空中交通的安全和效率明显受恶劣天气的影响，在机场起飞着陆滑行区域（TMA）尤其如此。在此区域，除了受天气影响之外，潜在的气象回避路线还受到空中交通管制的严格限制。因此气象回避模型 DIVMET 被开发出来。该模型给出一条建议路线，可以通过正在形成雷暴但尚未在里面实施任何空中交通管制的场地。DIVMET 被应用到香港国际机场的 TMA 区域，因为此处的空中交通管制（ATC）单位有兴趣通过模拟回避路线来提高管制员的工作量，尤其是用于管理进场飞机交通。ATC 单位对模拟的回避路线进行目视检查，其结果令人满意，但是商定了用实际观察到的路线对模拟情况进行定量验证。本文选择了香港 TMA 区域内有雷暴且交通严重扭曲时的两种真实恶劣天气情况。但是，进行任何验证之前的主要目标是识别仅仅受到天气影响但并未显示任何管制标志的路线。在飞行位置数据的基础上完成路线选择，选择若干着陆航班，并分析与标准进场路线的偏差。结果显示，272 架航班中大多数同时受到天气和管制的影响（60%），这突出表明空中交通管制员在恶劣天气下要安全有效地管理着陆交通是存在挑战的。只有少数受天气影响的航班（7%）未受到管制，可以用于验证。DIVMET 模拟路线被传给当地空中交通管制员，证明了这些路线是潜在切实的回避路线。在 TMA 区域内的 DIVMET 气象回避路线模拟有一定参考价值，但是进一步的模型开发必须将管制纳入考虑，至少要考虑停候、近道和减速。

关键词：雷暴回避；机场起飞着陆滑行区域；香港；水平环行；协同决策