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Traffic Meteorology

Aircraft route forecasting under adverse weather conditions

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Abstract

In this paper storm nowcasts in the terminal manoeuvring area (TMA) of Hong Kong International Airport are used to forecast deviation routes through a field of storms for arriving and departing aircraft. Storms were observed and nowcast by the nowcast system SWIRLS from the Hong Kong Observatory. Storms were considered as no-go zones for aircraft and deviation routes were determined with the DIVSIM software package. Two days (21 and 22 May 2011) with 22 actual flown routes were investigated. Flights were simulated with a nowcast issued at the time an aircraft entered the TMA or departed from the airport. These flights were compared with a posteriori simulations, in which all storm fields were known and circumnavigated. Both types of simulated routes were then compared with the actual flown routes. The qualitative comparison of the various routes revealed generally good agreement. Larger differences were found in more complex situations with many active storms in the TMA. Route differences resulted primarily from air traffic control measures imposed such as holdings, slow-downs and shortcuts, causing the largest differences between the estimated and actual landing time. Route differences could be enhanced as aircraft might be forced to circumnavigate a storm ahead in a different sense. The use of route forecasts to assist controllers coordinating flights in a complex moving storm field is discussed. The study emphasises the important application of storm nowcasts in aviation meteorology.

Keywords: route forecasting, adverse weather, storm nowcast, arrival management

1 Background

Hong Kong International Airport (ICAO code: VHHH, IATA code: HKG; in the following referred to as HKIA) annually serves 63.3 million passengers and 4.38 million tons of air cargo (2014). It is the third busiest international airport worldwide in terms of passengers with around 1,100 daily flights by more than 100 airlines. HKIA was the busiest air cargo airport with 4.4 million metric tons in 2014 (Airports Council International, 2015). Because of the proximity of the People's Republic of China, Hong Kong airspace has become complex over the years, seeing the development of equally complex air traffic control (ATC) and airport operations. Given the expected traffic growth in the Pearl River Delta in the coming decade, Hong Kong aviation experts started to investigate new solutions to cope with the situation and to provide a safe and efficient air service (NATS, 2008). One field with the potential for improvement is efficiency in adverse weather situations. Hong Kong airport is situated in complex terrain which makes it vulnerable to various adverse weather phenomena (Chan and Shao, 2007). A major risk is associated with strong wind and gusts in the lee of the Lantau Island mountain chain. Vortices are shed and drift across the runway and into the glide path, causing an unexpected shear threat for the pilots (Lei et al., 2013). Measures have been taken by the Hong Kong Observatory to understand and forecast the associated risks and also to warn pilots (Chan, 2010; Chan et al., 2011b). Convective weather is another major concern as, apart from hail, turbulence, icing and low visibility, strong winds in interaction with the terrain are associated with it (Chan et al., 2011a). Convective weather not only poses a significant risk to air traffic but also disturbs it significantly. Airport capacity is known to drop in thunderstorm conditions, with all the accompanying economic effects. A basic problem which pilots have to deal with is navigating around thunderstorm cells with a recommended safety separation of at least 10 to 20 NM (FAA, 2013). Under daylight conditions, storm cells are identified by the human eye and, or under poor visibilities, by the onboard radar. In practice, certain radar reflectivity threshold values (e.g. 42 dBZ) serve as a limit for the pilot to circumnavigate the storm cell and prevent him/her from flying through a storm. One major problem for pilots and air traffic controllers within the terminal manoeuvring area (TMA) is that pilots are forced on the one hand to fly along certain routes, normally the standard terminal arrival routes (STAR) and standard instrument departure

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routes (SID), but on the other hand are required to avoid storm cells. This leads to increased workload for controllers as interaction with the pilot increases substantially in the presence of storms. One specific problem is that any deviation from the planned standard route generates a delay downstream and postpones, for instance, the estimated time of arrival (ETA) at the airport. The overflight time at any requested waypoint, in the following also referred to as required time of arrival (RTA), such as at the final approach point is changed. Thus, the handling of arriving aircraft by the arrival manager (AMAN), a software-based controller support system, becomes more challenging. This problem makes it desirable to have a route forecast for vectoring the aircraft around storms and also over the mandatory waypoints until touchdown, when the aircraft enters the TMA. Conversely, for departing aircraft a weather conflict-free route to the planned TMA exit point would facilitate the controllers' work. Such a route forecast would automatically indicate the RTA at the requested and mandatory waypoints. The problem is demonstrably a four-dimensional one. Aircraft have residual flight times from entering the TMA until final landing of up to one hour. During that time storm cells move approximately 19 NM as their typical propagation speed is 10 ms^{-1}. In addition, cells may grow or shrink. Therefore, the controller has to coordinate the approaching and departing aircraft, which in itself is a highly dynamic process. Simultaneously, s/he has to monitor the weather, which is a dynamic process as well and limits operational flexibility considerably. It should be noted that weather conflict-free route forecasts also depend on the performance of an aircraft.

In this paper we investigate the potential for route forecasts under adverse weather situations and we compare those route forecasts with actual routes flown. We restrict our research to thunderstorms as the most important representatives of adverse weather, thus justifying our focus on them. We also look at the TMA and consider only landing and departing traffic, ignoring the en route traffic. The latter is seen to be affected on a different, larger spatial scale with less fixed regulations. Weather avoidance route forecasting for en route traffic will therefore be investigated elsewhere. For this study, we chose the TMA of HKIA as we have already performed some research there (Sauer et al., 2016) on which to build on. We evaluated landing and departing traffic over one day at HKIA when thunderstorms impacted the TMA and led to substantial storm avoidance manoeuvres (22 May 2011). In our study, we combine traffic simulations using the DIVSIM model with storm nowcasts of SWIRLS (short-range warnings of intense rainstorms in localised systems). The latter was developed by the Hong Kong Observatory and is already used for aviation purposes. DIVSIM is a coupled model with two components. DIVMET (Hauf et al., 2013) is a weather avoidance model where each aircraft is diverted around a given field of storms. The second component is NAVSIM, a traffic model developed at the University of Salzburg (Rokitansky, 2008; Rokitansky et al., 2007). NAVSIM simulates all traffic and moves the aircraft according to its specific performance profile around a storm along the route proposed by DIVMET. As a scenario we assume that each aircraft is provided with a time-dependent storm nowcast with a forecast horizon of approximately one hour either when entering the HKIA TMA or prior to departure from HKIA. The pilot is assumed to follow a route based on this weather forecast. In previous studies we have used the current weather at any instant of the flight but here we use a one-hour forecast issued at the time of entering the TMA or departing the airport, respectively. Thus, simulated aircraft circumnavigate forecast storms rather than actual storms at the respective flight time. We evaluate 22 selected flights where a weather impact was identified and compare the actual flown route (which is based on and in the following referred to as correlated position report data, CPR) with 1) the forecast simulated route which is based on weather nowcasts (referred to as NOW) and 2) a simulated reference route where observed storms were circumnavigated (referred to as OBS). For better understanding one should emphasise that case 2) uses actual observed storms, whereas in case 1) the forecast ones were circumnavigated. Case 2) is, therefore, based on a posteriori simulation. We summarise the results and give some findings concerning the model capabilities under the given assumptions. We will show that apart from weather ATC regulations play an important role in the HKIA TMA. This was shown in the paper by Sauer et al. (2016). If they can be determined and implemented in the DIVSIM model, the applicability of the model to HKIA would significantly increase. The main objective of the paper is to demonstrate the potential of combined storm nowcast and route simulations for future route forecasts under adverse weather conditions. Such model-based simulations would definitely support ATC in organizing safe and efficient arrivals and departures. This paper extends the ideas outlined by Sauer et al. (2016). In that paper, route simulations for the HKIA TMA were performed with actual observed storms at the respective times. Those simulations correspond to the above-mentioned a posteriori simulations of type 2). Here, in this paper, we will use nowcast storm data.

2 Objectives

In the light of the previous considerations, the objective of this paper is to demonstrate the potential of combined storm nowcasts and aircraft route-finding models, including the feasibility and usefulness of routes forecast by simulations. In detail, we will evaluate 22 simulated flights and compare them with observed flights. Furthermore, we will illustrate the need for a storm forecast as well as its impact on the route forecast quality. The effect of aircraft performance will be highlighted. Finally, any shortcomings and future necessary improvements will be described. The final objective is a tool to support the work of controllers within the Hong Kong TMA. That final tool, which has still to be developed, can be thought of as a software system which is operated by a controller and gives him/her likely flight routes and the expected overflight time at arbitrary but fixed waypoints for each aircraft entering the TMA or departing from the airport. It is referred to as a Weather (supported arrival) Manager (WX-MAN). One outcome of this study is also to define some key requirements for a WX-MAN.

3 The scenario – a weather-supported arrival manager, WX-MAN

The study adopted the following scenario where we hypothetically assume the existence of a future weather-supported arrival manager, referred to as WX-MAN. Whenever an aircraft is approaching the TMA, the controller starts the WX-MAN. The system initiates a route simulation for that specific aircraft. At the TMA entry time, a nowcast for the time span until landing is provided and according to that weather nowcast a weather diversion route is calculated. In Hong Kong, the current nowcast system is called SWIRLS. It is provided and operated by the Hong Kong Observatory (Cheng and Woo, 2014). The route forecast includes the RTA at one or more given requested waypoints, including touchdown at the airport. Similarly, for departing aircraft the complete route including necessary diversions until exit from the TMA is forecast at or prior to the time of takeoff. The input to the WX-MAN may be facilitated and automatised by feeding into the system planned and actual approaching aircraft call signs and positions well before they enter the TMA. For all planned routes deviation times, additional fuel, and sector occupancies can be calculated. The WX-MAN route forecast is offered to the controller, who may accept or reject it. S/he may also recalculate the routes by including corrections or regulatory procedures such as holdings, slow-downs and directs or shortcuts. The controller will also check potential conflicts with other aircraft along the proposed deviation route. The WX-MAN output may then be used by the controller to further organise the inbound or outbound traffic, and especially to feed the information into the common AMAN.

In this pilot study we will mainly show the usefulness of weather-affected route forecasts as the key element of a WX-MAN envisaged above. From the results we derive the key requirements for such a WX-MAN system.

4 Flight data

Twenty-two flight routes were selected out of several hundred flights on 21 and 22 May 2011, comprising 17 arrivals and 5 departures during a time span of 20 hours. The arrivals were categorised by eye inspection into (1) non-regulated but weather-affected (seven), (2) regulated but without weather impact (four), and (3) regulated and weather-affected (six). The categorisation scheme is illustrated in Figs. 1 and 2.

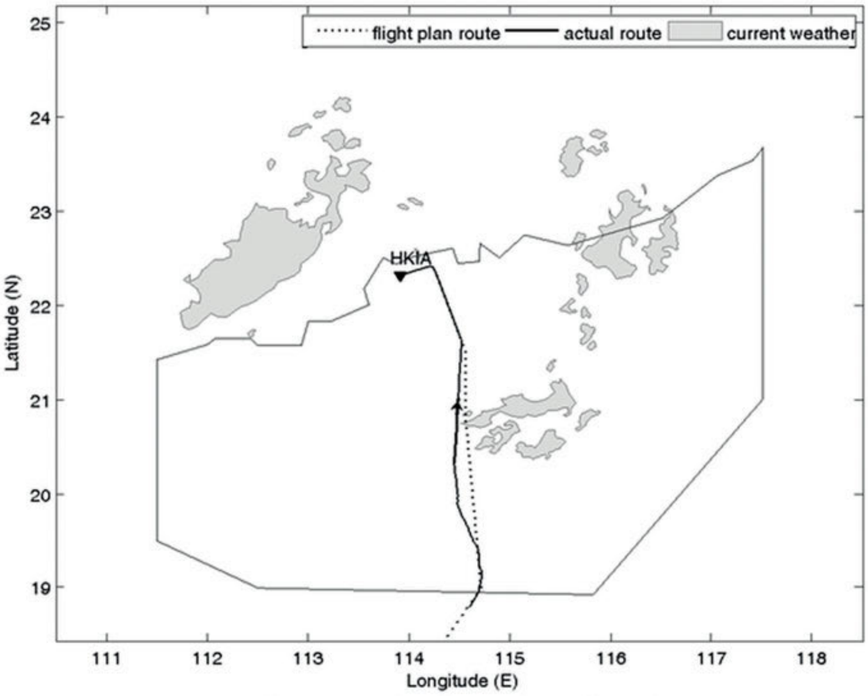
In a previous paper by Sauer et al. (2016) 272 inbound flights from nearly the same period were analysed and categorised. It was found that 68 % of them (= 184 flights) were weather-affected and correspondingly 32 % (= 88 flights) were not. Concerning ATC regulations, 85 % (= 231 flights) were regulated and 15 % (= 41 flights) did not show any sign of regulation. Interestingly, from the 184 weather-affected flights 163 flights (= 60 % out of 272) were regulated and only 21 flights (= 7 % out of 272) were not. The low last number implies that by far the majority of all weather-affected flights are also affected by ATC regulations. From that we can already conclude that ATC regulations have to be taken into account in advanced route forecasts.

Flight data were given as position data in five-second intervals. From the selected flights several further quantities were derived: TMA exit or entry time, departure time at the HKIA, departing airport for arrivals in Hong Kong, respective STAR routes, waypoints, TMA entry points, recognised regulations such as slow-downs, holdings, and shortcuts. Figs. 1b, 2a and 2b respectively give typical examples of holdings, shortcuts and slow-downs. Flight route data are summarised in Table 1.

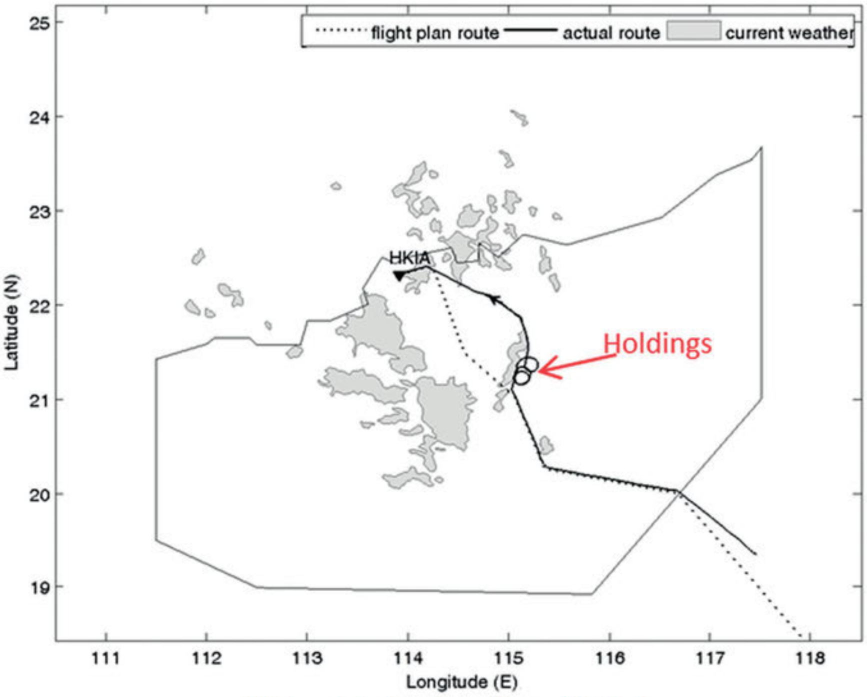
5 The nowcast model SWIRLS

Storm forecasts at a time scale of one hour – nowcasts – were provided by the nowcast system SWIRLS. The latter consists of a suite of combined models and algorithms developed for various purposes and scales (Cheng and Woo, 2014; Li and Lai, 2004; Li et al., 2000; Li et al., 2014), including one for aviation (Li and Wong, 2010). It advects recognised storm cells by the locally derived propagation speed based on an optical flow method (Yeung, 2012; Cheung and Yeung, 2012). The flow and thus the advection are inhomogeneous and allow for rotation and deformation of air masses. As with all nowcast systems, the generation of new cells is not possible. SWIRLS, however, simulates the intensity change with time, but does not yet cater for the growth and decay of cells (Li et al., 2014). SWIRLS provided storm nowcast data for the time frame 2200 UTC 21 May 2011 to 2200 UTC 22 May 2011. These data also include radar storm observations. Radar observations are essential for aviation under thunderstorm conditions. Over the years Hong Kong Observatory has developed a set of observational systems the output of which is ingested in SWIRLS (Chan, 2009; Chan and Hon, 2011; Chan and Lee, 2011).

From the given radar reflectivity fields weather polygons were extracted using a 36.5 dBZ reflectivity threshold value. The procedure was applied to both observations and nowcasts, yielding a total of 60,832 weather objects. It should be noted that in the route simulations, cells sometimes disappear and reappear. This is an artefact and is owed to the chosen thresholds for the derivation of weather polygons out of the radar reflectivity pixel field. The SWIRLS update



a) Non-regulated, weather-affected



b) Regulated and weather-affected

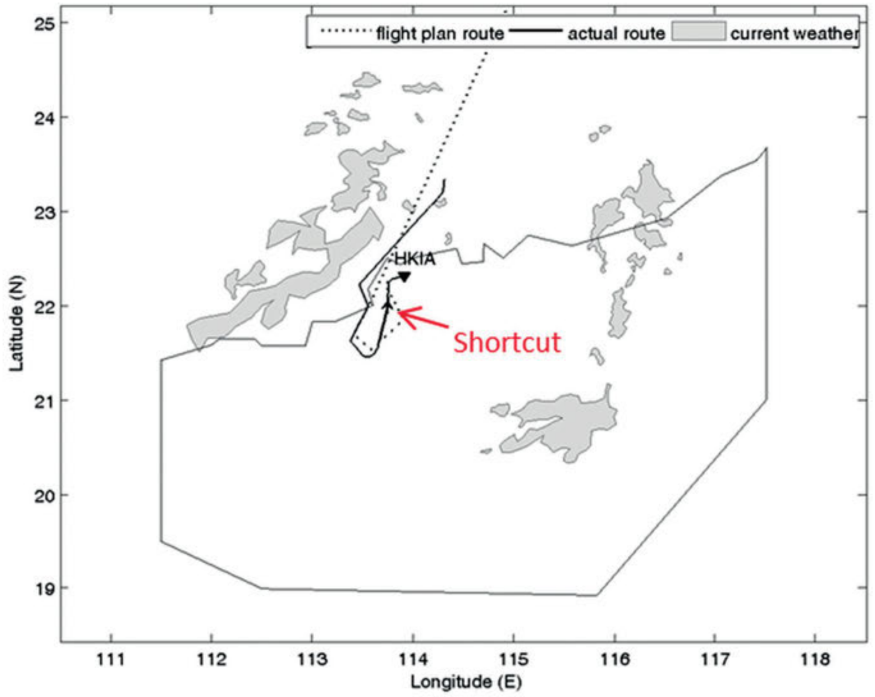
Figure 1: Categorisation scheme (1/2) for arrivals into: (a) non-regulated, weather-affected (Flight ID 10), and (b) regulated and weather-affected. The regulation measure 'holding' is highlighted (Flight ID 7). See also Fig. 2.

rate is six minutes and consequently route changes because of weather have an equal update rate. Thus, there might be sharp route changes because of the sudden appearance of storm cells ahead. It might also happen that a cell appears along a flight track that has already been passed, sometimes suggesting a supposed but not necessarily past crossing of that cell.

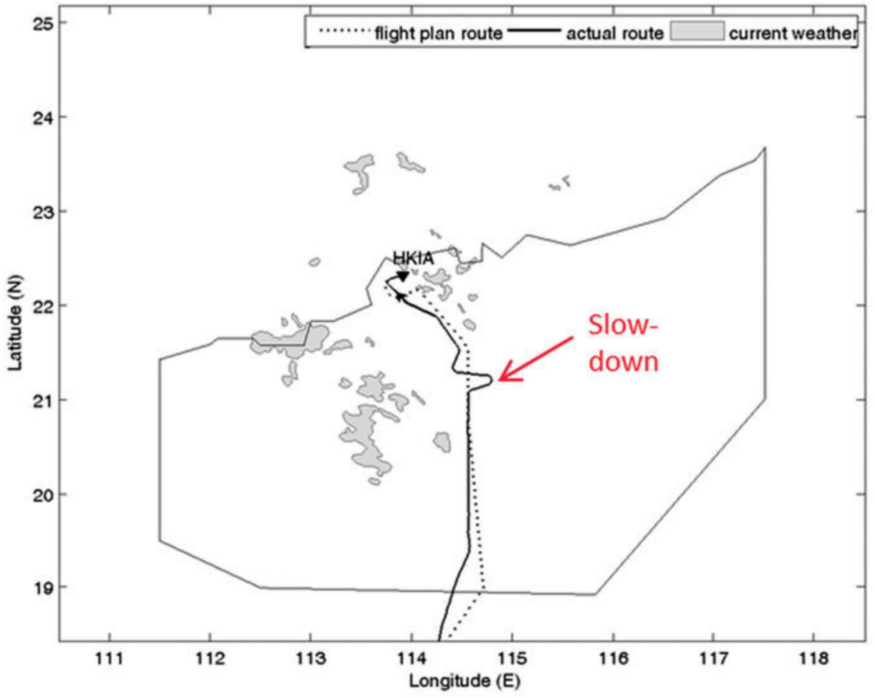
6 Traffic models and model set-ups

6.1 DIVMET

DIVMET was developed at the Leibniz Universität Hannover to investigate the behaviour of a pilot or a controller in conflict situations with adverse weather (Hauf et al., 2013). The model is also used for re-analysing



a) Regulated,non-weather-affected



b) Regulated,non-weather-affected

Figure 2: Categorisation scheme (2/2) for arrivals into: (a) regulated, non-weather-affected with a shortcut (Flight ID 11), and (b) regulated, non-weather-affected with a slow-down (Flight ID 0). See also Fig. 1.

flights under adverse weather situations. Prior to any simulation, weather polygons have to be extracted from radar data. The weather objects are then extended by a safety margin. To be able to adjust DIVMET to various situations, the safety margin is kept as a variable parameter typically ranging between 2 and 10 NM. The extended weather object is enclosed by a convex hull that finally represents the so-called risk area. In the simulation, this area has to be avoided by an aircraft if the object obstructs the current planned route. DIVMET decides whether to divert the facing object to the left or to the right based on an area criterion. If the in-risk area left of the planned route is larger than the right one, then the aircraft deviates to the right, and vice versa. Furthermore, DIVMET accounts for the planned route as long as possible and initiates the aircraft deviation from the planned route such that the required heading change is less than 35 °. This value was recommended by controllers as a rule of thumb. Similarly, the return capture fix is determined by the same angle criterion. DIVMET moves the aircraft by using a simple kinematic model with a constant true air speed (Sauer et al., 2013). For more details see Hauf et al. (2013), Hupe et al. (2014), and Sauer et al. (2016). To account for the flight performance of an individual aircraft, DIVMET is coupled to the air traffic model NAVSIM (Rokitansky, 2008). The coupled model is then referred to as DIVSIM and is described in more detail in Section 6.3.

6.2 NAVSIM

NAVSIM allows the simulation of up to 300,000 flights worldwide (Graeupl et al., 2012; Moertl, 2013). A simulation consists of three elementary steps, beginning with the input data (1). NAVSIM generates navigation and flight plan data from all known sources (airline data base, route data base, Aeronautical Information Service), and for all aircraft to be simulated, including all relevant ATM data for the latter. In our case, airline flight information is derived from the aircraft call signs. From all that information, the traffic demand can be derived for each flight consisting of a set of waypoints with associated overflight times. In addition, for each aircraft the performance is determined from an aircraft data base (BADA) for realistic simulation of any type of aircraft. These data include, for example, the aircraft characteristics relevant for take-off and landing, such as the climb rate. The simulation process (2) includes the display on a realistic ATC radar screen, the execution of the aircraft motion, and the simulation of flight management system (FMS) functions. The output data (3) are produced during the simulation. From the recorded aircraft positions, complex scenarios can be visualised and evaluated afterwards. The simulation tool provides a realistic representation of the entire air traffic from gate to gate (Rokitansky et al., 2007). NAVSIM can run in real time or up to 60 times faster in a fast-time mode, depending on the traffic amount.

6.3 Coupled DIVMET and NAVSIM model (DIVSIM)

In the coupled mode, NAVSIM simulates the routes and DIVMET checks for potential conflicts with weather objects. If there is a conflict, DIVMET calculates a complete route around the weather objects, respectively through the field of weather objects, from the current position to the final destination. If it is expected to initiate a deviation before the next weather update, DIVMET proposes the necessary waypoints to NAVSIM, either to circumnavigate the weather object, or, if there is more than one weather object, to navigate through the respective field of objects till the return-to-route point. NAVSIM then moves the aircraft along the proposed diversion with the specific aircraft and thus variable speed till new weather information is available. If nowcast data for weather objects are used, the situation is different. In a WX-MAN scenario with many aircraft handled simultaneously, NAVSIM is assumed to be run in real time. Then, when one aircraft enters the TMA, the real-time simulation is halted for a moment or runs in the background in a parallel mode, and, based on the nowcast data issued at that instant, a fast-time DIVSIM simulation is initiated which calculates the diversion route through the storm field till touchdown. This currently requires several tens of seconds of computing time, after which the real-time simulation is resumed until another aircraft enters the TMA. The computing time is expected to be reduced to one second in the near future. DIVSIM, therefore, is able to forecast the expected overflight time at a given waypoint or even the expected time of arrival at the airport, albeit the aircraft is still at the entry point.

For clarification, some DIVSIM features should be mentioned. DIVSIM in its current version does not check for aircraft-aircraft conflicts; neither does it search for conflict-free routes. It should, however, be noted that the planned routes used as input to DIVSIM can be assumed to be conflict-free. DIVSIM is based on published airspace and performance data. Thus, regulation measures such as holdings, slow-downs, and shortcuts/directs are not implemented as they are all introduced by a controller. It is, however, planned to model generic holdings, slow-downs, and directs which then can interactively be fed into the WX-MAN to generate each of these regulations into the simulations and change the routes accordingly. Resulting routes will show the respective structure at the intended locations and times. An open question is the exact fixing of both the exit and the return capture fix of the planned route, when an aircraft is circumnavigating a storm cell. Currently and as said above, the algorithm requires that the respective heading changes are less than 35 °. The latter value is based on discussions with pilots and ATC. Wind is also not included in the simulations. If the destination airport is covered by a storm or a risk polygon, and no diversion route can be calculated, the simulation will ignore the risk polygon and choose a direct way to the airport, along the planned route under the 35 ° heading change requirement. This situation appears very often in the investigated cases, both in observations and in simulations. This is in line with Rhoda and Pawlak (1999) who documented many cases in which thunderstorm penetrations occurred near airports. The simulation of a seemingly higher risk acceptance by pilots during their final approach to the runway lacks quantitative description, but the currently implemented rule does not seem to be too far from reality (see also discussion below in Section 7.4).

The necessary inputs for DIVSIM are: the planned route and its waypoints, the specific aircraft type, and weather data as radar reflectivity polygons. For real-time applications one should note that planned and actual

Table 1: Information on evaluated flights with simulation features: synchronization and discretization problem (SYN), apparent regulations like holdings (HD), slow-downs or zig-zag pattern (SD), weather-enforced shortcuts (SC/WX) and ATM-enforced shortcuts (SC), apparent heading change rule (HEAD), simulated shortcut at the TMA exit (EX), storm at Hong Kong airport or at final waypoints (STORM), and possible weather-enforced slow-down (SD/WX).

flight ID	departure airport	time at TMA entry/resp. at departure	entry/exit way point for TMA	arrival airport	holding HD shortcut SC slow-down SD weather WX	STORM y/n	EX	SYN	HEAD y/n	remarks
0	Singapore	01:40:40	CARSO	HKIA	SD SC	n	n	n	y	OBS and NOW significantly earlier because of HEAD-forced SC
1	Ho Chi Minh City	00:14:00	IDOSI	HKIA	SC/WX	n	n	n	y	NOW stays on FPL, OBS and CPR similar
2	Xiamen	00:03:10	DOTMI	HKIA		n	n	y	n	NOW closer to FPL
3	Chubu	03:24:25	ELATO	HKIA	SD	y	n	n	n	SD cleared weather near final approach
4	HKIA	00:55:00	SIKOU	Phuket	SC/WX	n	y	n	y	NOW saves most time
5	HKIA	01:15:00	ENVAR	New Chitose		y	y	n	n	NOW avoids storm while CPR and OBS cross it
6	HKIA	11:10:00	ENVAR	Taipei		y	y	n	n	CPR through storm, NOW avoids it
7	Manila	04:31:20	NOMAN	HKIA	HD	y	n	n	n	NOW provides good simulation, no HD
8	Dubai	12:03:30	SIERA	HKIA		y	n	n	n	NOW changes entry point, efficient route
9	Cairns	11:25:35	NOMAN	HKIA		n	n	y	n	CPR shifted entry point
10	Singapore	10:01:10	CARSO	HKIA		n	n	n	n	NOW and CPR in good agreement
11	Shenyang Taoxian	10:56:45	SIERA	HKIA	SD SC	n	n	n	n	CPR and NOW with slight differences
12	Kota Kinabalu	10:20:15	SABNO	HKIA		n	n	n	n	NOW efficient route
13	Singapore	12:15:35	CARSO	HKIA	SC	y	n	n	n	NOW good
14	HKIA	10:55:00	ENVAR	Taipei	SC	n	y	n	n	NOW good
15	HKIA	11:00:00	DOTMI	Shanghai	SC	n	n	n	n	NOW efficient
16	Taipei	12:29:00	ELATO	HKIA	HD	y	n	n	n	CPR finally through storm
17	Taipei	12:34:50	ELATO	HKIA	HD	y	n	n	n	CPR finally through storm
18	Tokyo	15:14:45	ELATO	HKIA	SD	y	n	n	n	HD helped CPR, OBS left TMA, NOW ignored storm
19	Bangkok	13:54:15	SIKOU	HKIA		y				No simulations possible because of over-complex storm situation
20	Sanya	13:56:30	IDOSI	HKIA	HD	y	n	n	n	Complex situation, CPR, NOW and OBS finally through storm
21	Manila	14:31:35	NOMAN	HKIA	HD	y	n	n	n	As for ID 20
Σ				17a 5d	4SD 5SC 5HD 2SD/WX	12	4	2	3	

flown routes may differ very often. Depending on the intention, it may become necessary to update aircraft positions to match the observed positions and to start a new route calculation from the updated positions.

6.4 Set-up of NAVSIM and DIVMET simulations

For both types of simulations the planned flight data have to be known. Based on the aircraft call sign of a given flight we conclude on that day-specific flight and on the departing airport (see Table 1). Together with the published aircraft type, NAVSIM generates a route from the departure to the arrival airport in compliance with the international air space structure. The departing time at the departure airport was changed such that the simulated time at the TMA entrance agrees with the observed ones. Along the route weather is ignored until Hong Kong TMA is reached. Then either the observed or the nowcast weather is used as an input for DIVMET, which then calculates deviations from the planned route according to the weather.

DIVMET provides a diversion route following the fixed prescribed procedures along the STAR routes with respective waypoints within the TMA. As mentioned previously, a key feature is the return-to-route assumption where we use a maximum heading change criterion of 35 °. Route simulations also include flight altitudes, respectively flight levels, although vertical height changes were not discussed in this study. Manoeuvres like the overflying of young growing cells and the underflying of cells, especially during final approach, are not included in the current simulation. For the time being weather avoidance simulations are two-dimensional.

SWIRLS radar reflectivity fields which include observations and six-hour forecasts/nowcasts are available as continuous pixelated two-dimensional fields. From these fields so-called weather polygons were derived. They consist of horizontal two-dimensional polygons whose reflectivity value is higher than a prescribed threshold value. Here we have chosen 36.5 dBZ. As a safety margin we assume 2 NM but vary that value for some studies as below to study the sensitivity of the results.

A key assumption is that each aircraft is assigned to one and only one nowcast when it enters the TMA. The nowcast itself consists of a time sequence of radar storm fields beginning at the respective entry time. Therefore, the weather is time-dependent, but the issuing time is fixed. This implies that the accuracy of the storm information degrades with time according to the nowcast quality. There is no update of the nowcast, though in reality, while the aircraft is flying, one will be issued every six minutes. The reason is that we want to have a route forecast available at the TMA entry time, and at that time the best weather information we have is the latest nowcast. The nowcast route calculation procedure is illustrated in Fig. 3 for various time steps and the respective forecast positions of the storm cell. In general, NAVSIM moves the aircraft along the waypoints of the flight plan (FPL) route if no alternative route is provided by DIVMET.

We discuss and compare the following routes and simulations.

1. Observed actual flown routes (in the following depicted in orange and referred to as CPR data): routes flown by the aircraft on 21 and 22 May 2011, based on reported data (CPR). They exhibit obvious regulation measures such as holdings (Fig. 1b), shortcuts (Fig. 2a), and slow-downs (Fig. 2b). As we try to answer the question of how well we can simulate a flight with the given models simulated flights are compared with these observed routes.

2. DIVSIM a posteriori simulations with observed storms (blue, also referred to as standard simulations and abbreviated as OBS). Here the route is determined by DIVMET according to the storm cell structure at the time when the aircraft is flying around the storm. NAVSIM moves the aircraft according to its specific performance. This type of simulation serves as a reference for identifying the nowcast error on the routes.

3. DIVSIM simulations with nowcasts (red, also referred to as nowcast simulations and abbreviated as NOW). NAVSIM provides the routes and moves the aircraft according to its specific performance whereas DIVMET calculates the circumnavigation around the nowcast storms. The route is planned according to the weather information at the time of TMA entry while OBS adjusts the route according to the actual weather.

As a sub-item we evaluated DIVMET simulations without involvement of NAVSIM (decoupled mode). Cells were circumnavigated with a constant true airspeed of 280 ms^{-1}, irrespective of the aircraft type.

7 Results

7.1 Evaluation

The evaluation of the flights is done by comparing the various routes qualitatively. We first look at the simulated flights NOW and OBS and compare them with the actual flown flights CPR. For that purpose, we present the simulations as click-through animation files. Each file shows the flight tracks travelled so far as well as their respective tracks within a six-minute interval. The latest aircraft position is marked. The routes are colour-coded as described above. At the end of each animation the complete routes are shown together with the weather objects (grey areas) on which the respective nowcast is based, i.e. the weather situation at TMA entry (for arrivals), or at departure time. Additionally, the actual weather (blue) and the nowcast polygons (red) are depicted for the latest time of landing or TMA exit, respectively.

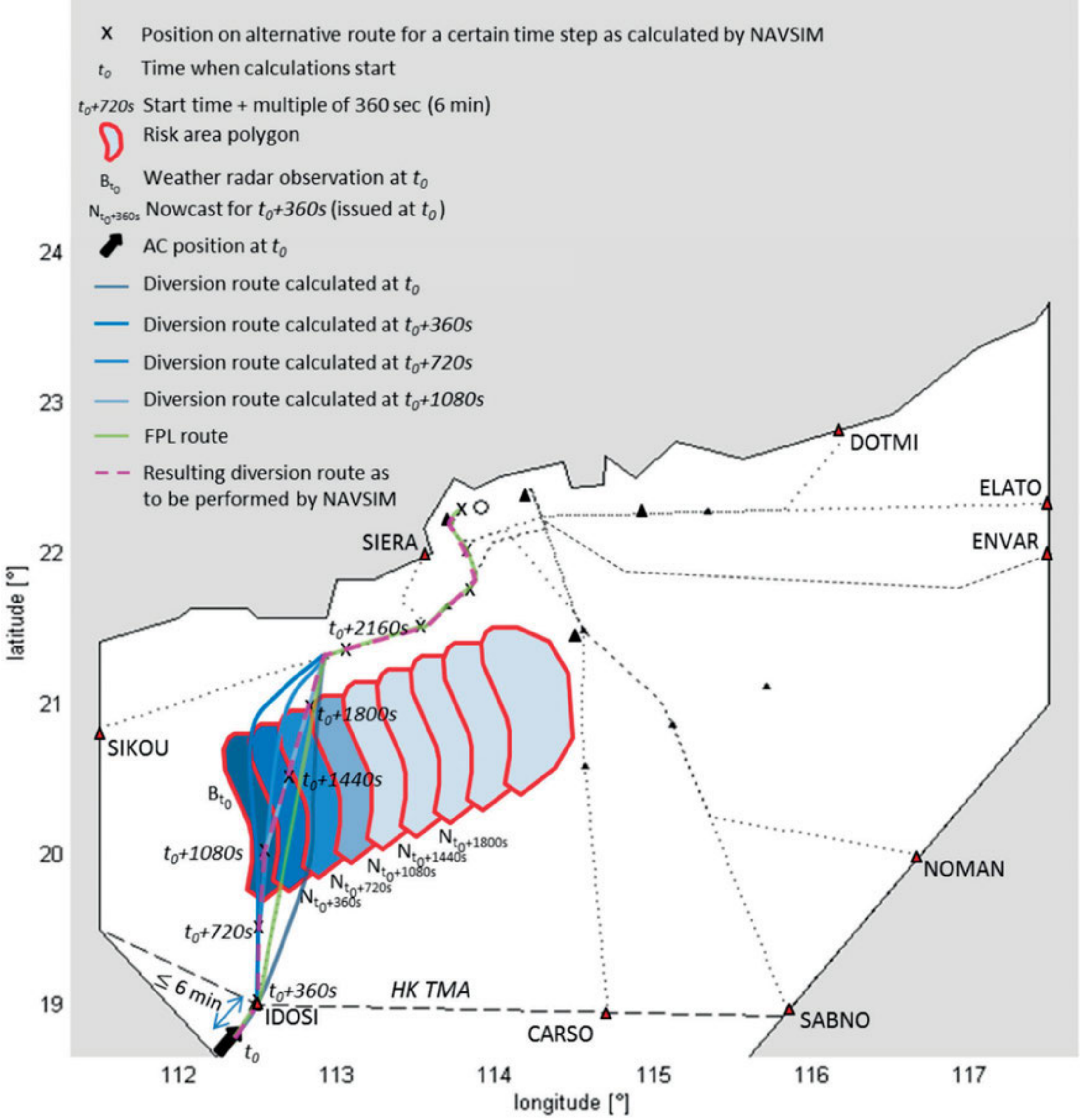


Figure 3: Illustration of the reactive response of the simulated flight path to nowcast weather objects. The planned route (green) is obstructed by an object ($B_{t,0}$) appearing at t_0 when the aircraft was up to six minutes ahead of the waypoint IDOSI. The sense of circumnavigation changes from right at t_0 to left at t_0 + 360 s. As the nowcast object moves to the upper right the subsequent routes adapt to the object's left side. DOTMI, ELATO, ENVAR, NOMAN, SABNO, CARSO, IDOSI, SIKOU, and SIERA denote entry and exit waypoints of the HKIA TMA.

By stepping through the files one can identify the simulated manoeuvres with reference to the actual and also to the nowcast storm positions. By visual inspection of the animated files several reappearing features can easily be identified. These features are listed in Table 1 and will be discussed in later sections. They concern and are referred to as: the synchronisation and discretisation problem (SYN), apparent regulations like holdings (HD), slow-downs, zig-zag pattern or S-turns (SD), weather (SC/WX) and/or ATC enforced shortcuts (SC), apparent heading change rule (HEAD), simulated shortcut at the TMA exit (EX), and storm at Hong Kong airport or at final waypoints (STORM). For illustration purposes one flight (ID 2) is discussed in detail. The other flights can be understood as straightforward from Table 1 and the animated files. Please note that the flight ID is chosen with regard to the NAVSIM simulation, starting with ID 0. Consequently, the 22nd flight is referred to as ID 21.

7.2 Detailed description of one flight (ID 2)

The description refers to the animated simulation (ANIM.ID 2) of flight ID 2.

Standard simulation OBS: two weather objects caused recognisable route differences between CPR, OBS, and NOW. The first one appeared immediately after TMA entry and the second one close to the final approach. The standard simulation OBS yields a route which complies with the FPL. It seems, however, to have crossed the first weather object. This is a combined synchronisation and discretisation problem (SYN) as the aircraft was already inside the polygon when the weather and the diversion route were updated. The problem might be overcome by monitoring the growth rate of storms, especially recognising strongly growing storms in their initial state. This would allow the issue of a new, earlier, weather update and subsequently a new route avoiding that rapidly growing storm. This feature, however, is not yet implemented in the weather object identifying algorithm. The second weather object was tightly bypassed along the planned route and neither crossed nor deviated though the pilot (CPR) obviously circumnavigated it.

Nowcast simulation NOW: the first weather object was ignored for the same reason as OBS. For the second weather object a diversion route was performed similarly to CPR.

0000–0005 UTC. TMA entry at the waypoint DOTMI and initiation of nowcast. The actual flight CPR leaves the FPL route to the left. As there is no weather object along the FPL route, both simulations OBS and NOW stay on route.

0006–0011 UTC. The simulations OBS and NOW found the aircraft within a rapidly growing storm. In this SYN problem, the flight would be continued along the FPL route. The pilot, however, recognised the storm, deviated to the left and rejoined the FPL route afterwards.

0012–0017 UTC. After continuing on the planned route, the actual flight CPR as well as the nowcast simulation NOW initiate a diversion to the left, while the standard simulation OBS, even with a safety margin of 2 NM does not recognise a problem and stays on the planned route. Both NOW and CPR deviate because of weather. The OBS simulation indicates a substantial weakening of the storm and allows the aircraft to continue on the FPL. In that case the difference between NOW and OBS, or the nowcast error, results in different routes. This error, however, should not be overvalued, as the pilot, for whatever reason, decided also to leave the FPL and circumnavigate the storm.

0018–0023 UTC. The nowcast simulation NOW has successfully avoided the conflict along the planned route and heads back to the FPL route, the STAR, thereby avoiding another nowcast object in agreement with the standard simulation OBS. The actual flight, however, remains to the left of the weather object and heads to a different waypoint on the STAR.

0024–0029 UTC. The actual flight CPR rejoins the planned route. All routes continue on the western approach standard routes.

0030–0035 UTC. The actual and the simulated flights arrive at the airport.

It is interesting to compare the landing times. The actual flight arrives almost three minutes behind the scheduled landing time which is 0033 UTC. This delay is probably caused by the circumnavigation of the two weather objects. Similarly, the route based on observed storms OBS arrives 31 seconds later than the one based on the nowcast storms NOW. It should be noted that the accuracy of absolute simulated landing times depends on the time synchronisation at TMA entry and on the assumed aircraft speed, which in the TMA is governed mostly by the traffic situation and to a lesser degree by the aircraft performance. The animated file gives a good visual impression of the synchrony of simulated and observed flights.

7.3 Overall impression of all simulated flights

We simulated 22 flights on 22 May 2011 between 0000 UTC and 1600 UTC and compared for each flight the flown route CPR, the flight plan FPL, the nowcast simulation NOW, and the standard simulation OBS. The first overall impression based on the animated files is that the NOW and OBS simulations provided reasonable solutions compared with the actual flown routes and the flight plan. There is, however, a large scatter from flight to flight. Table 1 lists and summarises certain repeated features within the simulations. Regulation by ATC was found for 12 flights with 4 slowdowns (SD), 5 holdings (HD) and 5 shortcuts (SC). A storm covered either the airport or the last two waypoints in 12 cases (STORM). The 35 ° heading change rule was always active in all simulations but triggered a larger deviation from the flight plan route FPL in three cases (HEAD). Two storms were crossed as the aircraft was found within a storm after a weather update (SYN). Four departing flights left the TMA not at the prescribed exit waypoint (EX). In the following we discuss each of these features. Naturally, any one of them will change the arrival times at certain waypoints including the estimated landing time and the estimated time of TMA exit point overflight. Thus, the qualitative route differences will dominate any quantitative simulation evaluation, which is why we concentrate in this evaluation on the former, though the forecast of any overflight time is of the greatest importance for a later application, e.g. by the WX-MAN.

For simple weather configurations the agreement between the simulations (OBS and NOW) with the actual flown route (CPR) is quite good. For more complex situations differences increase, especially when the airport or the last two waypoints ahead of it are covered by storms (STORM feature), and for one extremely complex situation when storms were found nearly everywhere in the whole TMA and a reasonable route could not be found (ID 19). We emphasise especially flight ID 7 where, in view of the intended WX-MAN, the simulation proposes a route through a gap between two storms. The actual flight, however, remains on the planned route, is forced by the storm to perform two

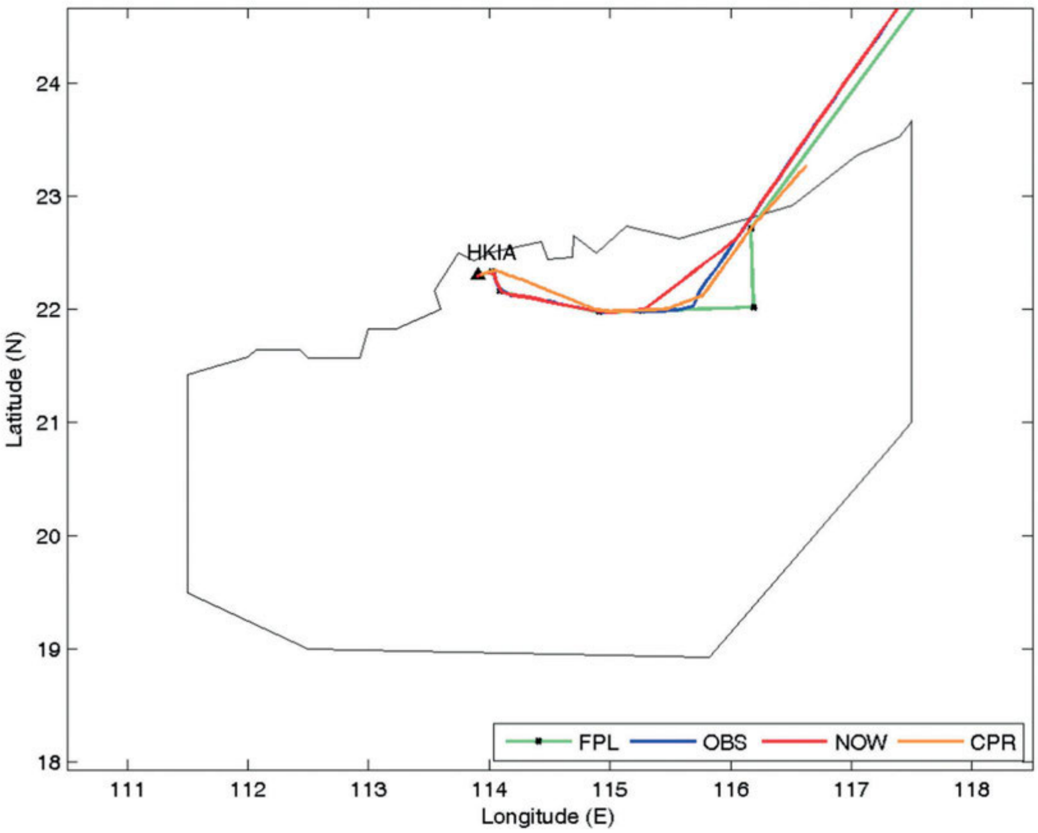


Figure 4: Final trajectories for flight 15 (departure) with a shortcut of the actual flight immediately after departure (in brown) and weather-related diversions shortening the flight two waypoints before leaving the TMA (weather not shown).

holdings, and nevertheless has to circumnavigate the storm (ANIM.ID 7).

7.4 Characteristic features of the simulations

Regulations: of the 22 flights four departure and ten arrival routes show signs of regulation. Just by visual inspection of the flown routes one can identify slow-downs, holdings, and shortcuts. Slow-downs appear as zig-zag patterns, while holdings reveal a typical race track shape. Shortcuts shorten bent routes. An investigation of EUROCONTROL and FAA (2014) worked out that in Europe and the USA actual flights are more efficient than their corresponding flight plan routes. In other words, very often pilots ask for a shortcut or a direct. The latter term is often used by controllers and is typically applied from the actual position to the border of the sector the controller is responsible for. Obviously, this is done to shorten the flight and, consequently, to increase efficiency and to save fuel. From the CPR data of the 22 flights, one can see that in the Hong Kong TMA shortcuts are not uncommon (5 SC, see Table 1). Shortcuts are flown to reduce delay from previous flight phases or just to make use of free capacities in the airspace and thus increase efficiency, as, e.g., can be seen for flight ID 15 immediately after take-off (Fig. 4, see also ANIM.ID 15). Shortcuts may also go hand in hand with avoiding a risk area (Fig. 4). While an aircraft is circumflying a storm, very often a shortcut is initiated and it is therefore uncertain whether in general a shortcut is enforced by ATC (SC) or by deviating weather (SC/WX; see Table 1). Furthermore, very often a shortcut is asked for after the pilot has deviated a storm. Instead of returning to the planned route directly, a more remote waypoint is requested (see ANIM.ID 19). Depending on the situation, the pilot maintains the heading and flies parallel to the original route.

Knowing the STAR structure within the Hong Kong TMA, Sauer et al. (2016) additionally detected changes from one STAR to another, preferred holding areas, and changes in the TMA exit or entry points.

All these regulations are part of the controller's portfolio to guarantee safe arrivals and departures as well as an efficient flow structure. All of these regulation measures are put in place by a controller, mostly while the aircraft is within the TMA, and therefore cannot be simulated on the basis of a priori knowledge. Thus, in relation to the WX-MAN, each regulation measure has to be modelled and implemented in DIVSIM. It can then be activated interactively by the operator for a specific aircraft at any instant. As regards this future development, it is important to note that NAVSIM allows for such an interactive individual request for an aircraft during real-time simulation. Heading changes, flight level changes, route changes, and speed changes can be executed manually by an operator/controller. Thus, NAV-

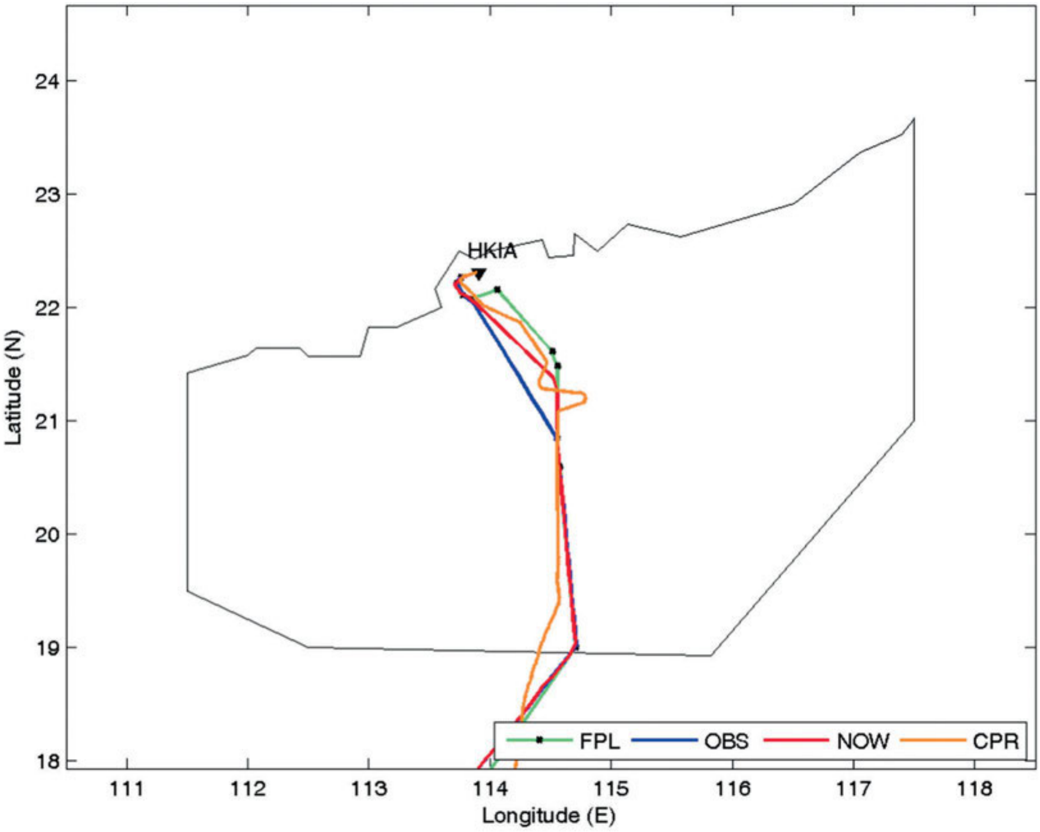


Figure 5: Final trajectories for flight 0 (regulated arrival). Illustration of the 35 ° heading change simulation criterion leaving out requested waypoints after having avoided a storm (weather not shown).

SIM is already prepared for the implementation of regulation measures. A slow-down, for example, has to be prescribed by a number of parameters, such as lateral range, requested time delay, and a return-capture-fix ahead. Similarly, STAR changes require an exit point of the current route and an entry point of the new route.

One further important rule for Hong Kong concerns the prohibited overflight of mainland China territory, except on agreed air routes. Note that there is no single flight violating that rule. It is a straightforward modelling exercise to develop such modules and implement them into DIVMET and NAVSIM.

In summary, however, the implementation of regulatory procedures is beyond the scope of the current study but they significantly influence the overflight times at waypoints, the landing time at the airport, and the flight duration. As a consequence, any quantitative comparison of simulated and observed flights becomes meaningless because of the imposed regulations. In this study, we have therefore avoided quantitative comparison and focused on the qualitative differences between the various routes.

Impact of the 35 ° heading change criterion: an important feature of the DIVMET algorithm when determining a deviation route is the decision as to when the original planned route has to be left. Currently a heading change criterion is implemented. The planned route is kept till the latest predefined waypoint at which the heading change required to circumnavigate the next weather object remains smaller than 35 °. This prevents abrupt direction changes. A similar criterion holds for returning to the route. The point where the original route is joined is shifted downstream until the required heading change there is smaller than 35 °. Three obvious cases can be determined in the simulations (see Table 1). In Fig. 5, the blue aircraft leaves the planned route although there are two further waypoints to go before the weather object is encountered (ANIM.ID 0). A heading change at the later diversion points would be larger than 35 °. This angular criterion may lead to large deviations in the case of large objects. An example is given in Fig. 6 (ID 4, see also ANIM.ID 4). The heading change criterion here requires that the deviation route is initiated at the second waypoint after departure. After the second last waypoint before TMA exit has been checked but revised for returning as the heading change rule would have been violated, the simulations offer a direct way to the TMA exit point. Meanwhile, the actual flight deviates less while the pilot avoids several storms. The forecast diversion routes are likely to be revised by the controller as they cross a transition route for arrivals. In reality, the 35 ° rule can be overruled by ATC advice (see e.g. ID 12; ANIM.ID 12). Thus the strict application of the 35 ° heading change rule should be considered as an option for an operator to change interactively in a future WX-MAN.

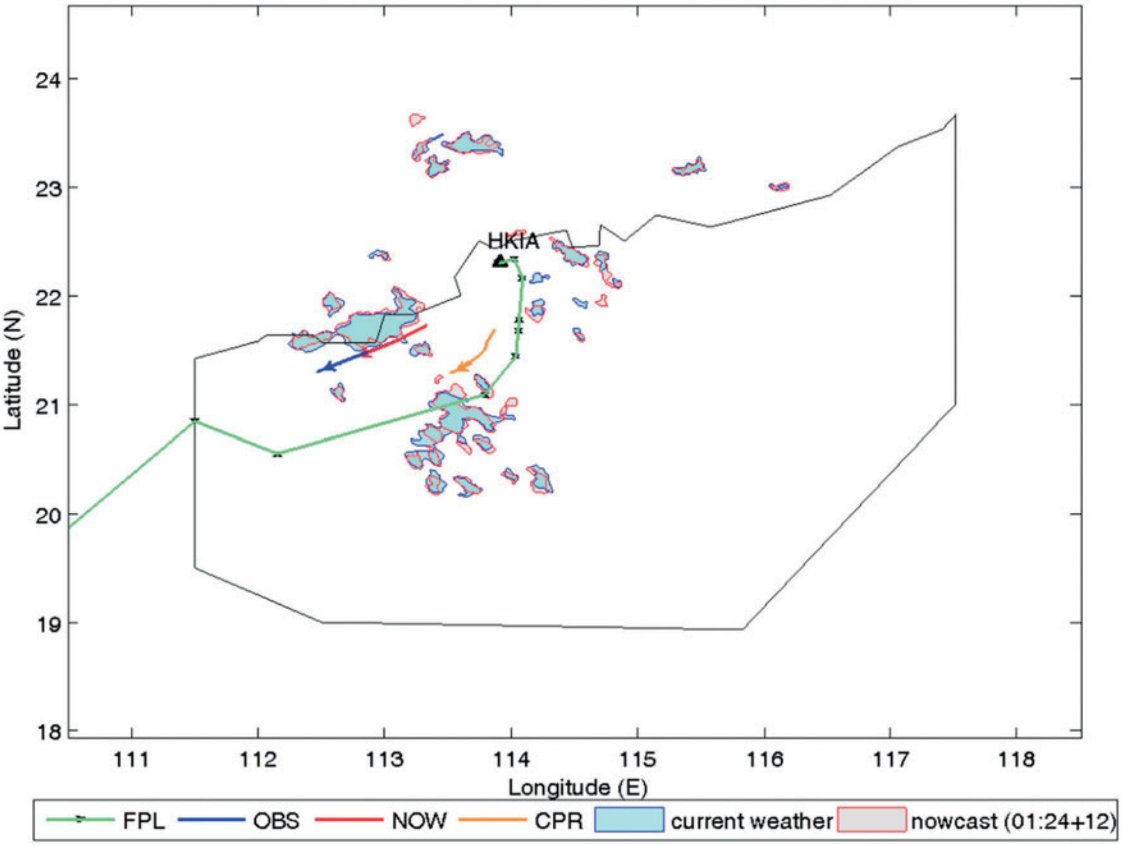


Figure 6: Example for simulations with a large deviation from the FPL owed to the 35 ° heading change criterion. Flight ID 4 is illustrated between 0136 and 0141 UTC.

Airport and/or final waypoints covered by storms (STORM): regarding landing traffic, Rhoda and Pawlak (1999) identified the conflict whether pilots should follow the mandatory landing procedures or avoid storms. At greater distances from the TMA and en route pilots typically avoid any storm, following international recommendations (FAA, 2010; NATS, 2010), while closer to the airport during descent the number of storm penetrations increases significantly. Operational landing requirements, with the only option being to abort the landing procedure, seem to make pilots accept a somewhat higher storm penetration risk. In essence, operational requirements seem to outweigh weather-related safety concerns in some way. This was already observed by Sauer et al. (2016) for the Hong Kong TMA and is confirmed by the current study. During landing as well as during take-off storms were penetrated (ID 5, 6, 16, 17, 20, 21), mostly close to the airport, i.e. during the final approach or immediately after take-off (ANIM.ID 5, ANIM.ID 6, ANIM.ID 16, ANIM.ID 17, ANIM.ID 20, ANIM.ID 21). However, it should be noted that what appears as a storm crossing could also be the underflying of a storm. Nevertheless, the latter action has considerable hazards such as downdrafts, lightning, and hail, to mention but a few. It is up to the pilot to proceed with the landing procedure or to perform a missed approach. There is no general rule for resolving that conflict of aims and simulations have to come up with a feasible solution. If the airport or the last two waypoints are covered by a storm, DIVSIM simply follows the planned route till touchdown. The same holds for departing traffic. In reality, however, various responses to that situation can be identified. Pilots try to gain some time by means of holdings or slowdowns, which helped in two cases as the weather cleared slightly to allow a penetration-free approach (ID 3, 18; ANIM.ID 3, ANIM.ID 18). In other cases pilots hesitated and searched for safe solutions but did not succeed and finally had to penetrate the storm for landing anyway (ID 20, 21). The simulation of such situations is currently not within the realms of possibility (ANIM.ID 20, ANIM.ID 21).

Weather update-related synchronisation problems (SYN): radar-based weather information is provided with a certain update rate. In the case of SWIRLS, every six minutes a new nowcast is disseminated. Weather, therefore, changes stepwise every six minutes but remains constant in between. In contrast, simulated aircraft move at smaller time steps in the order of three seconds. Because of these synchronisation differences some typical problems appear (referred to in this paper as SYN). Aircraft circumnavigate storms though they may have already disappeared. On the other hand, a new storm appears and an aircraft is suddenly covered by it (see ID 2). The latter problem may be overcome when the nowcast system checks for rapidly developing storms, e.g. by monitoring the radar reflectivity values or by adding satellite information and checking for rapidly changing cloud top temperatures. In SWIRLS, however, these features are not implemented yet and, consequently, in some cases aircraft seem to ignore a storm and fly through it. Once an aircraft is within a storm, DIVSIM continues along the last determined route and exits the storm on that route (ANIM.ID 2).

DIVSIM-triggered shortcut at the TMA exit: although the simulations usually follow the FPL along prescribed waypoints, in some cases this rule is violated (ID 4, 5, 6, 14). Here, DIVSIM proposes a shortcut when exiting the TMA (see ANIM.ID 4, ANIM.ID 5, ANIM.ID 6, ANIM.ID 14). Though this may sometimes be allowed by ATC, here it is a simple simulation error which will be corrected with the next program update. We also should note that the change of the TMA entry point in flight with ID 8 resulted in a more efficient route compared with CPR (ANIM.ID 8). This change was made deliberately to illustrate the simulation possibilities of avoiding risk areas beyond the TMA.

7.5 The role of storm nowcast precision

Within the framework of this study we did not intend to do an extensive evaluation of the SWIRLS capability. Rather we note here some obvious features. As has been documented by various authors (e.g. Li et al., 2000; Li et al., 2014), the quality of the SWIRLS nowcast system is in general quite good. The nowcast methodology suits forecasts up to one hour quite well and is used for the aviation-related version of SWIRLS. Differences, as with all nowcast systems, concern the generation of new cells, the decay of existing ones, the uncertainty in propagation speed, and also positive or negative growth in the intensity and shape of existing cells. In the given case with update rates of six minutes any newly emerging cell will be detected and then consequently forecast. In the case which is pursued here, however, the nowcast is not updated with routes calculated at the time of TMA entry. Thus, compared with observations, the nowcast will always differ in the number of new cells and generally will degrade with time. We have also noted that slight propagation speed errors may trigger a different direction of circumnavigation. If this happens, route differences become significant. In general, for small nowcast errors the route differences remain small, except when changing the direction of circumnavigation is enforced. The movement of individual storm cells within the one hour from TMA entry to final touchdown clearly illustrates the necessity to use nowcast data for route forecasts. Ignoring the weather development worsens the results.

8 Summary

We have demonstrated the simulation capability to forecast the route for an aircraft as soon as it enters the Hong Kong TMA. The storm development from that time on is provided by a SWIRLS nowcast. Using this nowcast, a route was simulated till touchdown at the airport, based on a prescribed safety distance to the storm cells. For the route simulation we used the DIVSIM model package which determines the deviation route (via DIVSIM) and the traffic environment in which the individual flight is embedded (via NAVSIM). DIVSIM routes based on a nowcast were compared with routes based on actual observed storms at the relevant times. The objective of this comparison was to test the quality of the SWIRLS nowcast. It was found that the nowcast quality is good and its quality loss with time is acceptable within the one-hour forecast frame. It should be noted that the use of observed storms can only be done a posteriori as at the time of TMA entry future observations are not available. Ignoring nowcasts and using a fixed, static weather pattern at the entry time is not recommended as route changes owed to the moving and developing weather pattern were often observed and cannot be ignored.

We also compared the simulated routes with the actual flown routes. As expected, only a few (seven) out of 17 arrivals investigated showed no signs of regulatory procedures imposed by air traffic control. A recent study by Sauer et al. (2016) on the recognisable weather effect in the Hong Kong TMA with a larger data set revealed that only in 15 % of all cases was a route weather-impacted without any regulation. As regulatory procedures we have identified shortcuts, holdings, slow-downs, and change of STAR routes (not discussed) but also included aircraft avoidance manoeuvres and sequencing procedures. The respective flight patterns were not part of the simulations. Consequently, simulated routes differ substantially from the observed ones for such cases. Holdings and slow-downs automatically delay a flight, causing a shift in overflight time and landing time. In addition to the regulation measures, local empirical and organisational rules exist. One important rule is the closed air space over mainland China for weather-related deviations. The existence of other rules which may also depend on the actual traffic situation can be assumed, though we did not attempt to identify them. If those measures are to be part of the route forecast, they have to be defined, validated by comparison with observed flights, expressed as an algorithm, and then implemented in the DIVSIM simulation model. This is considered a straightforward programming task. In contrast, the enforcement of regulations is initiated by a controller in real-time in response to traffic requirements and would therefore be much more difficult to take into account. Traffic interactions, especially conflicting situations with other aircraft, however, are not simulated by the DIVSIM software in the current study. Thus, the use of simulated regulation patterns is seen in an interactive simulation environment where, for instance, the controller can activate one or more of the regulations for each simulated aircraft.

With each route forecast, overflight times at all waypoints are provided automatically by DIVSIM. A comparison of simulated and observed overflight times was hindered by the fact that the related routes differed and consequently an overflight time shift was automatically built in. Furthermore, the data show that pilots tended to recover lost time during weather-related diversions by adjusting the subsequent flightpath and speed. Conversely, pilots had to slow down because of preceding aircraft and/or on ATC advice as part of the sequencing procedure prior to landing. We summarise that (1) overflight times and landing time can be forecast, (2) it could not be proven but it is reasonable to assume that the forecast simulated overflight times can be used successfully for ATC purposes (AMAN etc.), (3) simulated overflight times depend crucially on route changes, true air speed variations, and, to a lesser degree, on aircraft performance.

Any overflight time shift may confront the pilot with a different weather situation downstream. This may lead to a different direction of circumnavigation of, e.g., a confronting weather cell. Time-dependent weather, therefore, may amplify an initial time difference considerably. As the initial overflight time shift may already be caused by a diversion route, we conclude that at least in cases with highly variable weather the route determination is a strongly nonlinear problem.

The route forecast problem for departing aircraft differs in some aspects from those arriving. Immediately after departure there is no possibility of avoiding a storm penetration. Therefore, either the take-off is delayed by the pilot or the aircraft flies through the storm. Compared with arrivals, underflying is no option for departures as the ATC enforced climb rate is higher than the equivalent sink rate during landing. As the aircraft in most cases starts with the maximum possible load, climb rate changes are limited. Thus, overflying of even shallow cells ahead is difficult to achieve. In contrast to arrivals, there are no slow-downs or holdings. For departing aircraft, however, the exit point for leaving the TMA may deviate from the planned one. Thus, there is a higher emerging degree of freedom with time and storms may be circumnavigated more easily.

Complex weather situations in combination with weather updates need to be investigated in more detail to enhance the simulations' performance.

A test was performed and DIVMET alone simulated the deviation routes without using NAVSIM and thus without using aircraft specific performance data and variable true airspeed. The test proved that DIVSIM simulations are superior to pure DIVMET simulations (not shown).

All of the aforementioned general objectives can be confirmed.

- Weather conflict-free route forecasts can be provided prior to departure for departing aircraft and also at the time of TMA entry for arrivals.
- Reliable real-time route forecasting as soon as an aircraft enters the TMA is possible.
- Simulated forecast routes are good estimates of actual flown routes.
- The overflight time of a given fixed waypoint can be forecast as soon as an aircraft enters the TMA, but depends significantly on the length of the earlier deviation route, the ATC or pilot-induced speed changes, and the aircraft performance. Knowledge about the chosen aircraft speed will increase the accuracy of overflight time estimates.
- Route forecast accuracy can be increased when instead of a generic aircraft performance individual aircraft performances are used in the simulations.
- Forecast/nowcast of the storm field is necessary. Its accuracy is crucial for the simulated deviation route.

From a meteorological point of view, this paper reveals another interesting and important but still challenging application of storm nowcast. However, the SWIRLS capability should be enhanced to simulate generation and decay of cells. It should also provide an increased update rate in the case of rapidly growing storm cells.

9 Outlook

The authors of this pilot study suggest the use of route simulations as a supplementary tool for air traffic controllers. Therefore, they propose a software system referred to as the WX-MAN, and list, in the following, its key requirements and features and the research and development to be done.

- The WX-MAN is based on NAVSIM coupled with DIVMET (DIVSIM).
- The WX-MAN will be operated by local controllers within a TMA, e.g. at Hong Kong ATC.
- Shortcuts, directs, STAR changes, holdings, no-go zones, and slow-downs have to be defined, cast in algorithmic form, programmed, and implemented. They can be activated during a fast- or a real-time simulation. Validation of these formalised regulation measures by comparison with observed ones would be required.
- Empirical rules concerning the penetration of a storm for landing or departing have to be investigated and implemented.
- Similarly, the application of the 35 ° heading change rule should be extended such that it can be cancelled by the controller during a simulation and overruled by an immediate return-to-route option or other advice.
- A user interface for the WX-MAN should be developed allowing for active control of all simulated aircraft. This includes heading changes, speed changes, and setting of new waypoints among the previously mentioned features.
- The planned arriving and departing traffic is simulated in real time in a background mode.

- The WX-MAN should be coupled with ATC to allow for a real-time and continuous update of aircraft positions. This enables the WX-MAN to update the arrival routes and achieve higher accuracy when aircraft enter the region of interest, especially before entering the TMA.
- The WX-MAN should be coupled with a nowcast system such as SWIRLS to receive one-hour nowcasts at any time.
- The WX-MAN provides a radar screen-like monitor displaying the inbound and outbound traffic, especially the route forecasts at the time of TMA entry and departure, respectively.
- The WX-MAN should be coupled with an AMAN.
- The sole purpose of the WX-MAN is to reduce the controller's workload and thereby to increase safety and efficiency within the TMA.
- The WX-MAN has to be continuously evaluated and improved.

In summary, it can be stated that the current study, together with the outlook, clearly identified relevant issues and viable improvements in ATM procedures based on nowcasting and subsequent flight routing in the TMA, not only for Hong Kong but for other weather-affected airports worldwide as well. Weather remains an important issue for aviation but the implementation of weather forecasts is capable of reducing the impact significantly, thereby increasing the safety and efficiency of future air traffic.

List of abbreviations

AMAN	arrival manager
ATC	air traffic control
ATM	air traffic management
BADA	base of aircraft data, developed by EUROCONTROL
CARSO	waypoint of Hong Kong Terminal Manoeuvring Area (see Fig. 3)
CPR	correlation position report data; aircraft position data derived from ATC surveillance systems, normally updated every one to three minutes
DIVMET	adverse weather diversion model
DIVSIM	adverse weather diversion model DIVMET coupled with the air traffic simulation model NAVSIM
DOTMI	waypoint of Hong Kong Terminal Manoeuvring Area (see Fig. 3)
ELATO	waypoint of Hong Kong Terminal Manoeuvring Area (see Fig. 3)
ENVAR	waypoint of Hong Kong Terminal Manoeuvring Area (see Fig. 3)
ETA	estimated time of arrival
EX	simulation feature: shortcut at the Terminal Manoeuvring Area exit
FMS	flight management system
FPL	flight plan (route)
HD	simulation feature: holding
HEAD	simulation feature: apparent 35 ° heading change rule
HKG	IATA code for Hong Kong International Airport
HKIA	Hong Kong International Airport
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ID	internal DIVSIM identification number of flights, ranging from zero to 21
IDOSI	waypoint of Hong Kong Terminal Manoeuvring Area (see Fig. 3)
NATS	National Air Traffic Services; main air navigation service provider in the United Kingdom
NAVSIM	air traffic simulation model
NOMAN	waypoint of Hong Kong Terminal Manoeuvring Area (see Fig. 3)
NOW	simulated route forecasts with dynamic nowcast storms
OBS	a posteriori route simulations with dynamic observed storms
RTA	required time of arrival
SABNO	waypoint of Hong Kong Terminal Manoeuvring Area (see Fig. 3)
SC	simulation feature: shortcut
SC/WX	simulation feature: weather enforced shortcut
SD	simulation feature: slow-down
SID	standard instrument departure
SIERA	waypoint of Hong Kong Terminal Manoeuvring Area (see Fig. 3)
SIKOU	waypoint of Hong Kong Terminal Manoeuvring Area (see Fig. 3)
STAR	standard terminal arrival routes
STORM	simulation feature: storm at Hong Kong airport or at final waypoints
SWIRLS	short-range warnings of intense rainstorms in localised systems; a Hong Kong Observatory nowcast system
SYN	simulation feature: combined synchronization and discretization problem
TMA	terminal manoeuvring area
UTC	coordinated universal time
VHHH	ICAO code for Hong Kong International Airport
WX-MAN	envisioned AMAN with adverse weather-avoiding route forecasts

Appendix

Supplementary Table: All flight routes are available at https://doi.pangaea.de/10.1594/PANGAEA.869476. All data can be downloaded.

HKIA: Hong Kong International Airport
black polygon: Hong Kong Terminal Manoeuvring Area
blue polygons: observed storms (wx) at the assigned time
red polygons: nowcasts (nc)

Routes:

- green (FPL): flight plan route
- blue (OBS): DIVSIM a posteriori simulation with observed storms
- red (NOW): DIVSIM simulation with nowcasts
- orange (CPR): actual flown route

Animation	Name of data file	Data file size		Legends to the animations
Flight ID 0	ANIM.ID 0.ppsx	244 KB	Power Point animation	Flight ID 0
Flight ID 1	ANIM.ID 1.ppsx	214 KB	Power Point animation	Flight ID 1
Flight ID 2	ANIM.ID 2.ppsx	210 KB	Power Point animation	Flight ID 2
Flight ID 3	ANIM.ID 3.ppsx	249 KB	Power Point animation	Flight ID 3
Flight ID 4	ANIM.ID 4.ppsx	250 KB	Power Point animation	Flight ID 4
Flight ID 5	ANIM.ID 5.ppsx	220 KB	Power Point animation	Flight ID 5
Flight ID 6	ANIM.ID 6.ppsx	240 KB	Power Point animation	Flight ID 6
Flight ID 7	ANIM.ID 7.ppsx	385 KB	Power Point animation	Flight ID 7
Flight ID 8	ANIM.ID 8.ppsx	188 KB	Power Point animation	Flight ID 8
Flight ID 9	ANIM.ID 9.ppsx	285 KB	Power Point animation	Flight ID 9
Flight ID 10	ANIM.ID 10.ppsx	264 KB	Power Point animation	Flight ID 10
Flight ID 11	ANIM.ID 11.ppsx	193 KB	Power Point animation	Flight ID 11
Flight ID 12	ANIM.ID 12.ppsx	302 Kb	Power Point animation	Flight ID 12
Flight ID 13	ANIM.ID 13.ppsx	253 KB	Power Point animation	Flight ID 13
Flight ID 14	ANIM.ID 14.ppsx	277 KB	Power Point animation	Flight ID 14
Flight ID 15	ANIM.ID 15.ppsx	212 KB	Power Point animation	Flight ID 15
Flight ID 16	ANIM.ID 16.ppsx	320 KB	Power Point animation	Flight ID 16
Flight ID 17	ANIM.ID 17.ppsx	318 KB	Power Point animation	Flight ID 17
Flight ID 18	ANIM.ID 18.ppsx	264 KB	Power Point animation	Flight ID 18
Flight ID 19	ANIM.ID 19.ppsx	246 KB	Power Point animation	Flight ID 19
Flight ID 20	ANIM.ID 20.ppsx	325 KB	Power Point animation	Flight ID 20
Flight ID 21	ANIM.ID 21.ppsx	300 KB	Power Point animation	Flight ID 21

References

Airports Council International, 2015: 2014 World Airport Traffic Report. – ACI World, Montreal, Canada.

Chan, P.W., 2009: Performance and application of a multi-wavelength, ground-based microwave radiometer in intense convective weather. – Meteorol. Z. **18**, 253–265. DOI:10.1127/0941-2948/2009/0375.

Chan, P.W., 2010: LIDAR-based turbulence intensity calculation using glide-path scans of the Doppler LIght Detection And Ranging (LIDAR) systems at the Hong Kong International Airport and comparison with flight data and a turbulence alerting system. – Meteorol. Z. **19**, 549–563. DOI:10.1127/0941-2948/2010/0471.

Chan, P.W., K.K. Hon, 2011: Application of ground-based, multi-channel microwave radiometer in the nowcasting of intense convective weather through instability indices of the atmosphere. – Meteorol. Z. **20**, 431–440. DOI:10.1127/0941-2948/2011/0276.

Chan, P.W., Y.F. Lee, 2011: Application of a ground-based, multi-channel microwave radiometer to the alerting of low-level windshear at an airport. – Meteorol. Z. **20**, 423–429. DOI:10.1127/0941-2948/2011/0275.

Chan, P.W., A.M. Shao, 2007: Depiction of complex airflow near Hong Kong International Airport using a Doppler LIDAR with a two-dimensional wind retrieval technique. – Meteorol. Z. **16**, 491–504. DOI:10.1127/0941-2948/2007/0220.

Chan, P.W., K.K. Hon, S. Foster, 2011a: Wind data collected by a fixed-wing aircraft in the vicinity of a tropical cyclone over the south China coastal waters. – Meteorol. Z. **20**, 313–321. DOI:10.1127/0941-2948/2011/0505.

Chan, P.W., K.K. Hon, D.K. Shin, 2011b: Combined use of headwind ramps and gradients based on LIDAR data in the alerting of low-level windshear/turbulence. – Meteorol. Z. **20**, 661–670. DOI:10.1127/0941-2948/2011/0242.

Cheng, T.-L., W.-C. Woo, 2014: "SWIRLS" Nowcasting System. Education Resources. – http://www.hko.gov.hk/education/article_e.htm?title=ele_00448. Last access: 2 May 2016.

Cheung, P., H.Y. Yeung, 2012: Application of optical-flow technique to significant convection nowcast for terminal areas in Hong Kong. – The 3rd WMO International Symposium on Nowcasting and Very Short-Range Forecasting (WSN12), Rio de Janeiro, Brazil. Hong Kong Observatory, Reprint 1025.

EUROCONTROL, FAA, 2014: Comparison of ATM-related operational performance: U.S./Europe. – Final Report, EUROCONTROL, Brussels, Belgium.

FAA, 2010: Weather-related Aviation Accident Study 2003–2007. – Technical Note, Federal Aviation Administration, Washington, DC.

FAA, 2013: Advisory Circular No: 00-24c, Federal Aviation Administration, Washington, DC.

Graeupl, T., B. Jandl, C.-H. Rokitansky, 2012: Simple and Efficient Integration of Aeronautical Support Tools for Human-In-the-Loop Evaluations. – In: Proc. Integrated Communications Navigation and Surveillance Conference, Herndon, Virginia, F4/1–F4/9.

Hauf, T., L. Sakiew, M. Sauer, 2013: Adverse weather diversion model DIVMET. – J. Aerospace Operations **2**, 115–133. DOI:10.3233/AOP-130037.

Hupe, P., T. Hauf, C.-H. Rokitansky, 2014: Case Study of Adverse Weather Avoidance Modelling. – In: Proc. of the 4th SESAR Innovation Days, Madrid, Spain.

Lei, L., P.W. Chan, Z. Li-Jie, M. Hui, 2013: Numerical simulation of terrain-induced vortex/wave shedding at the Hong Kong International Airport. – Meteorol. Z. **22**, 317–327. DOI:10.1127/0941-2948/2013/0439.

Li, P.W., E.S.T. Lai, 2004: Applications of radar-based nowcasting techniques for mesoscale weather forecasting in Hong Kong. – Meteorol. Appl. **11**, 253–264. DOI:10.1017/S1350482704001331.

Li, P.W., W.K. Wong, 2010: Development of an Advanced Aviation Nowcasting System by Including Rapidly Updated NWP Model in Support of Air Traffic Management. – 14th Conference on Aviation, Range, and Aerospace Meteorology, Atlanta, Georgia. 93rd AMS Annual Meeting. Hong Kong Observatory, Reprint 873, Hong Kong.

Li, P.W., W.K. Wong, K.Y. Chan, E.S.T. Lai, 2000: SWIRLS – An Evolving Nowcasting System. – Technical Note No. 100, Hong Kong Observatory, Hong Kong.

Li, P.-W., W.K. Wong, P. Cheung, H.-Y. Yeung, 2014: An Overview of Nowcasting Development, Applications, and Services in the Hong Kong Observatory. – J. Meteor. Res. **28**, 859–876. DOI:10.1007/s13351-014-4048-9.

Moertl, J., 2013: NAVSIM Overview/Aviation Competence Center. – In: ESA/Iris Public Information Day, 4D-Aerospace, Salzburg, Austria.

NATS, 2008: Airspace and runway capacity study phase 1, Deliverable 0.6, Final Report. – http://info.threerunwaysystem.com/pdf/en/NATS_phase1.pdf. Last access: 9 May 2016.

NATS, 2010: The effect of thunderstorms and associated turbulence on aircraft operations. – Technical Note AIC: P 056/2010, UK Aeronautical Information Service, Hounslow, Middlesex.

Rhoda, D., M. Pawlak, 1999: An assessment of thunderstorm penetrations and deviations by commercial aircraft in the terminal area. – Project Report NASA/A-2, MIT Lincoln Laboratory, Lexington, Massachusetts.

Rokitansky, C.-H., 2008: NAVSIM – Advanced Air Traffic Simulation Tool for CNS/ATM Performance Evaluations. – In: USAF CNS/ATM Conference, Tampa, Florida.

Rokitansky, C.-H., M. Ehammer, T. Graeupl, 2007: NEWSKY – Novel Simulation Concepts for Future Air Traffic. – In: Proc. 1st CEAS European Air and Space Conference, 611–618. Deutscher Luft- und Raumfahrtkongress, Berlin, DGLR Bonn.

Sauer, M., L. Sakiew, T. Hauf, P. Hupe, 2013: Some Applications of the Adverse Weather Diversion Model DIVMET. – 16th Conference on Aviation, Range, and Aerospace Meteorology Austin, Texas. 93rd AMS Annual Meeting.

Sauer, M., T. Hauf, L. Sakiew, P.W. Chan, S.-M. Tse, P. Hupe, 2016: On the Identification of Weather Avoidance Routes in the TMA of Hong Kong International Airport. – J. Zhejiang University SCIENCE A **17**, 171–185. DOI: 10.1631/jzus.A1500186.

Yeung, H.Y., 2012: Recent developments and applications of the SWIRLS nowcasting system in Hong Kong. – The 3rd WMO International Symposium on Nowcasting and Very Short-Range Forecasting (WSN12), Rio de Janeiro, Brazil. Hong Kong Observatory, Reprint 1024, Hong Kong.