WORLD METEOROLOGICAL ORGANIZATION

# AVIATION RESEARCH AND DEVELOPMENT PROJECT PHASE 2 (AvRDP2)

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## Progress Report

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## EXECUTIVE SUMMARY

The Aviation Research and Development Project, Phase 2 (AvRDP2) reached its half-way point in 2023. This report provides some background, a status of the project, and plans for the last two years of the project (ending in December 2025). AvRDP2 has established two primary flight routes along which different nowcasting and forecasting products related to convective weather hazards are being developed, tested and evaluated. The shorter route is between Hong Kong and Singapore (HKG-SIN) and the longer route is between London, UK, and Johannesburg, South Africa. The specific hazards are the occurrence of thunderstorms, turbulence induced by those thunderstorms (in cloud or near cloud) and the occurrence of high altitude ice crystals in large concentrations that can compromise aircraft operation. Research is ongoing regarding the utility of ensemble forecasts for flight planning such that alternative routes are identified that efficiently avoid the worst convective hazards. Research on improved nowcasting techniques is also assessing products from satellite and ground-based radar sources that provide consistent time and space coverage along flight routes. Blending of these ensemble and nowcast techniques is being tested to find robust methods that retain the best of both the artificial intelligence generated nowcasts and forecasts generated from numerical models. The remainder of the project will examine the efficacy of products and provide recommendations for how such products can be adapted for other major flight corridors along which thunderstorms are a concern.

## 1. BACKGROUND

Aeronautical meteorology is critical to the safe, efficient, regular and sustainable operation of the global aviation system and can help to reduce the environmental impact of flights. A key concept in the Global Air Navigation Plan (GANP) is Trajectory Based Operations (TBO) which requires fit-for purpose streams of observed and predicted data of high temporal and spatial resolution that are suitably updated, along the entire flight trajectory, from taxi and take-off, through ascent, en-route (cruise) and descent phases, to landing and gate arrival phases. According to the global survey on aeronautical meteorological service provision conducted in 2016/17, majority of the services are provided by the national meteorological and hydrological services (NMHS). A long-term plan for aeronautical meteorology (LTP-AeM) prepared by CAeM and published by WMO in 2019 provides a framework for the progressive transformation from a conventional "product-centric" approach to a modern "information centric" approach to MET service provision that is appropriate for risk management and other needs as articulated through ICAO's GANP and an ICAO 'White Paper' of 2018 titled 'Future Aeronautical Meteorological Information Service Delivery'. In response to the need to develop better real-time tools to avoid convective weather hazards along the entirety of flight routes, many of which traverse remote regions, and to develop a consistent methodology that ensures spatial and temporal consistency in advisories across adjacent FIRs, the second phase of the Aviation Research and Development project (AvRDP2) was launched in 2021. This project is intended to further the scientific advancement and apply the scientific findings and new methodologies to service delivery ('science-for-services') to demonstrate the achievable benefits to aviation users.

**Project vision**: "Leveraging advances in meteorological observing, nowcasting and forecasting research to enable the delivery of risk-based, hazard-impact information services that fully meet aviation users' needs."

**Project Mission**: "The overall mission of the Project is, through international collaboration, to develop, demonstrate and quantify the benefits of improvements to the forecasting of **significant convection and associated hazards.** The Project will also devote special attention on developing and demonstrating advancements in probabilistic forecasting and statistical methods (for providing confidence information and other assessments for the end-users), as well as on forecast verification and validation."

**Time Frame:** The Project will last 5 years from 2021 to 2025 with periodic reviews of progress to be conducted after an Initial phase (in 2021) and at mid-term in late 2023. This document constitutes this mid-term progress report.

**Project Scope:** Gate-to-gate avoidance of convective hazards along selected flight routes. The Project intends to demonstrate the concepts of research-to-operations and science-for services with the full value chain through collaboration between Research Board, INFCOM and SERCOM. It focuses on airport city-pairs to demonstrate the gate-to-gate use of advance aviation meteorological information in the future aviation operations environment. AvRDP2 requires seamless meteorological information from the take-off, ascent, cruising, descent, until landing phase to support the whole safe and efficient flight operations for the whole trajectory. It fits well with WMO's seamless earth system initiative, where "seamless" refers not just to the timescales from minutes to days in this project, but across earth system domains spanning the whole value chain from observations to users' benefits. Opportunity would be taken to evaluate the impact of observation, including the benefits of additional observations in the terminal area. While weather hazard information from the World Area Forecast System (WAFS) is available for flight planning, this has to be supplemented by advanced nowcasting information for tactical and pre-tactical decisions. The project studies the blending of nowcasting information on the above-mentioned key meteorological hazards with global and regional models using advanced techniques such as the use of Machine Learning methodology. Special attention is placed on the advancement of the use of ensemble techniques in probabilistic forecasting and statistical methods for assessing the uncertainly/confidence of the information, as well as on verification and validation.

In the beginning of the project, numerous city pairs were considered for investigation. Because of the practical constraints of time available and contributions of project participants, two airport pairs were selected: London Heathrow Airport (LHR) and Johannesburg OR Tambo Airport (JNB), and Hong Kong (HKG) – Singapore (SIN). The HKG-SIN flight route is located in the tropics and is prone to convection year-round and along the entire flight route. Its relatively short duration (4-5 hours) means that nowcasting is relevant for flight planning. The LHR-JNB route spans over 80 degrees of latitude, requires more than 11 hours of flight time, and includes two mid-latitude regions and a large expanse of the tropics over the African continent, part of which produces deep convection at all times of the year. The LHR to JNB route is also distinct from the HKG to SIN route due to the limited observations for much of the flight path over continental Africa. Flight planning for LHR-JNB must rely on operational numerical weather prediction forecasts out to approximately 18 hours lead time, in addition to real-time information. Ensemble or probabilistic data are the key to help capture the uncertainty in this convective forecast data, which may not be such an issue for shorter haul flights such as on the Hong Kong (HKG) to Singapore (SIN) route. The World Area Forecast System (WAFS) provides a global source of convection forecast data for aviation that can be used to help make aircraft routing decisions. Currently this information is deterministic, but future WAFS data (in 2027) will have probabilistic information and so this development product has been examined here.

**Governance and Accountability:** The project is under the lead of WWRP under Research Board (RB) with SC-AVI under SERCOM as close partner and Infrastructure Commission (INFCOM) as the secondary partner. A community advisory group (CAG) links WMO with the International Civil Aviation Organization (ICAO), IATA (airlines), IFALPA (pilots), ACI (airports), IFATCA (air traffic controllers), CANSO (air navigation service providers) and other relevant experts to ensure the Project is steered towards the global air traffic management vision conveyed in the ICAO Global Air Navigation Plan (GANP) over the coming decade. A cross-cutting Scientific Steering Group (SSC) involving relevant WWRP/WGs, Core Projects, as well as SC-AVI/ET-WCS from SERCOM oversees the Project. The SSC is also responsible for the content in this report.

## 2. RESULTS TO DATE

This section considers progress for the two flight routes selected for AvRDP2 (London (LHR) to Johannesburg (JNB), and Hong Kong (HKG) to Singapore (SIN)) as well as a complementary modeling study on convectively induced turbulence (CIT).

### 2.1 LHR-JNB

Most of the work on this airport pair has focussed on (i) severe convection including associated problems with windshear, lightning and even hail, and (ii) High Altitude Ice Crystals (HAIC) thus far. Ground-based observations are sparse, so any nowcasting capabilities for much of the en-route phase of flight would rely on geostationary satellite observations. This has been looked at in terms of the High-Altitude Ice Crystals (HAIC) hazard.

### 2.1.1 Use of probabilistic NWP data to reduce risk of aircraft encountering convection

The probabilistic convection WAFS product proposed for 2027 has been developed and is running in a real time trial at the UK Met Office (Anderson et al., 2023). This product is based off the Ensemble Prediction of Oceanic Convective Hazards (EPOCH) system developed at the National Center of Atmospheric Research (NCAR). This data was explored in the context of the LHR to JNB route to analyse how it could be used to help in decision making processes (Vertrees, 2023). Figure 1 shows a possible example product that calculates the mean and maximum probability of a Cb cloud with a height greater than 30kft along the route. The average values are low as this includes all the way points where the probability is zero, but this could be re-calculated for only non-zero points. The table in Figure 1 also shows the accumulated distance along the route where the flight is exposed to any non-zero probability of Cb cloud heights above 30kft. Additionally, a graphical representation demonstrates how such a probability varies along the route. In this example flight route 2 has a generally more favourable outlook for flying with less exposure to severe convection than flight route 1. Figure 2 shows the two flight routes together with probabilistic convection forecast information. This data can also be used at different lead times, to create a composite map covering the time windows that match up with the approximate time along the flight way points. The user may like to see the hazard forecast displayed on a map so that they can get an appreciation of the spatial location and extent of the convection, in addition to the route statistics. One of the debates in this project is how much information is necessary to expose to the customer to make weather routing decisions without 'swamping' the customer with too much weather information alongside all the other non-weather information to decide the route of flights.

| | Mean | Maximum | Distance (km) |
|---|---|---|---|
| 🟩 Flight 1 | 0.034 | 0.722 | 1120 |
| 🟥 Flight 2 | 0.009 | 0.278 | 680 |

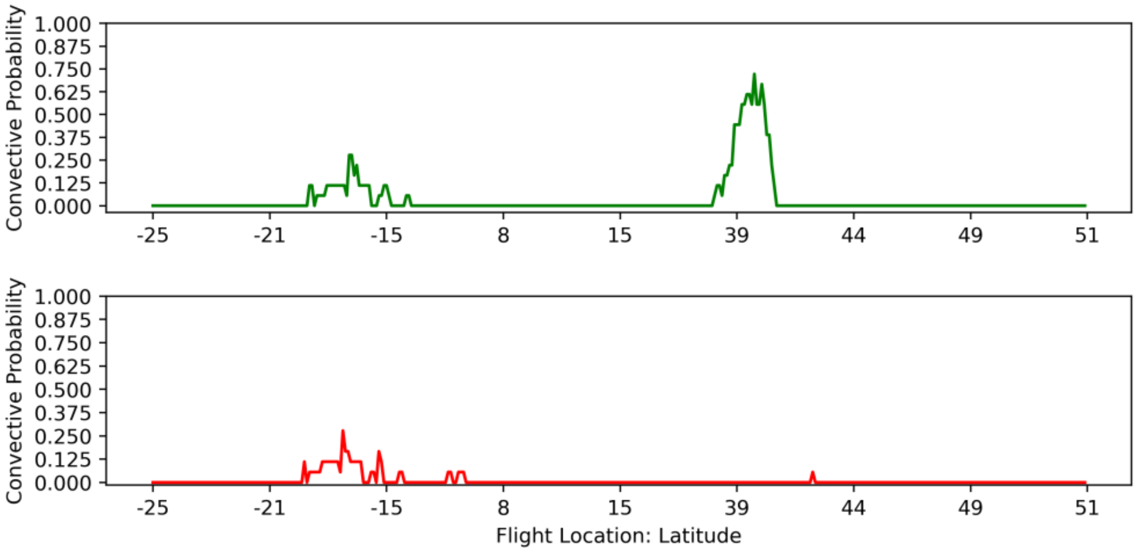


*Figure 1: Comparing route statistics of convective cloud heights exceeding 30kft for two northbound routes on 6th February 2023, using the 12Z model run.*

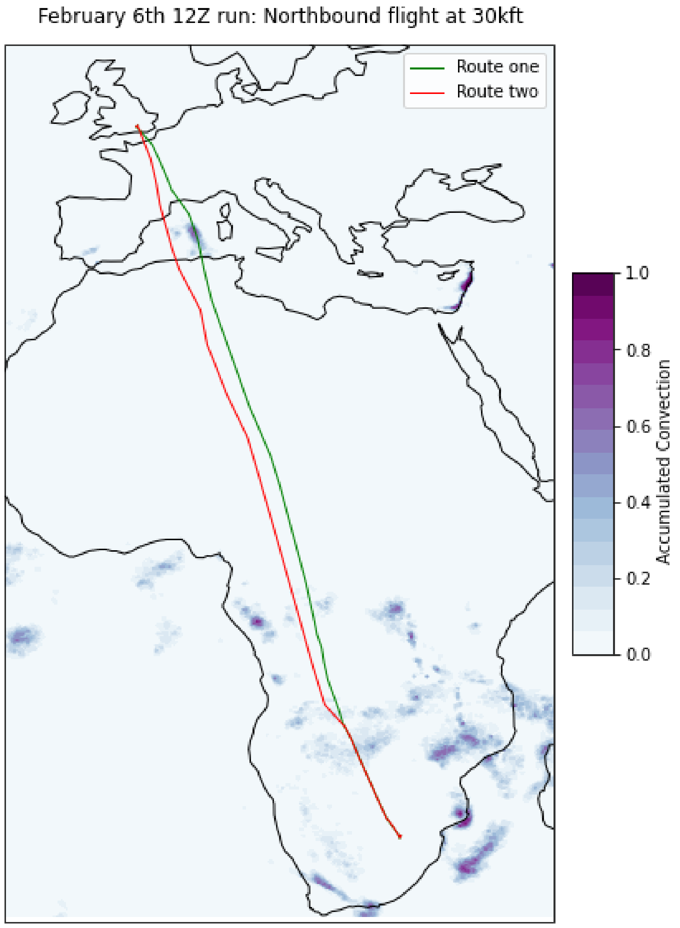


*Figure.2: Map visualisation of the convective forecast and two possible northbound route options.*

### 2.1.2 Use of nowcast information

Along a long-haul route, nowcasting information is essential for providing real-time guidance about convection activity for tactical in-flight decisions and terminal area information around the times of take-off and landing. AvRDP2 is exploring different nowcasting capabilities over Europe and Africa and determine which are most appropriate (and feasible regarding timescales, resource, etc.) to potentially bring into a prototype for the London Heathrow to Johannesburg flight route.

There are a number of radar-based nowcasting products in Europe which are used to detect and track convective cells. Many of these are only available at a regional level so only cover parts of Europe and/or small sections of the flight route. The Met Office's systems utilize the radar-based cell tracking based on the Thunderstorm Identification, Tracking, Analysis, and Nowcasting (TITAN) method (Dixon and Wiener, 1993) and adapted to include a forward-prediction element for the cells, as explored by Muñoz et al. (2018). This identifies and tracks convective cells in 5-minute intervals and produces forecasts out to 1 hour ahead. This is only available over the UK so would only be useful in the phase of flight for departure or arrival into Heathrow. Over South Africa a regional radar network is available that can be utilised to cover the terminal area and ascent/decent phase of the flight route into/out of Johannesburg. As with the Met Office, the South African Weather Service (SAWS) also makes use of the TITAN method to identify and track convective cells (6-minute intervals) with forecasts 1 hour ahead (although 2-hour forecasts are possible). Several algorithms are available to detect weather elements, such as hail and rainfall. Doppler velocity measurements can also be used to derive wind profiles.

EUMETSAT have developed a variety of satellite-based products for convective nowcasting. The RDT-CW (Rapidly Developing Thunderstorm - Convection Warning) product was developed by Météo-France in the framework of the EUMETSAT Satellite Application Facility (SAF) and uses geostationary satellite data (Meteosat Second Generation (MSG) for this project) to identify thunderstorms and their characteristics. The Met Office runs a local version of RDT which could be utilized in this project, although this focuses on the UK and Europe so a version encompassing more of the route would be preferable (e.g. from the Global NWC-SAF). SAWS also runs a local version of the EUMETSAT Nowcasting (NWC) SAF for Southern Africa (up to the equator) with regional NWP (Unified Model 4.4km) as input. Over South Africa and neighbouring countries the SAWS lightning data is also ingested into the SAF products (Gijben and de Coning, 2017). The RDT cell objects are presented according to the phase of the cells (growing, mature, and decaying) and 15-, 30-, 45- and 60-minute forecast tracks are available for the cells.

High Altitude Ice Crystals (HAIC) continue to be of concern to aviation users operating in particular parts of the world (Rugg et al., 2021). It is possible to have satellite, nowcasting and NWP products that indicate areas along a flight route that are susceptible to HAIC. Whilst it is hard to have a rich source of aircraft observations for HAIC on a daily basis there have been flight campaigns and reporting initiatives that have helped calibrate some of the prototype products.

Like many forecasting centres, the Met Office has a probabilistic HAIC detection and nowcasting capability. This can be used in a similar way to the probabilistic convection forecast data to assess the likelihood of encountering the hazard along different flight routes, as demonstrated by Wang Ying (2023). Figure 3 shows the HAIC likelihood along three possible tracks of the LHR to JNB route. These routes are listed in terms of low, medium and high HAIC risk values (again calculating the mean probability of HAIC along each route), shown in the blue (0.004), orange (0.019) and red (0.046) tracks, respectively. The map in Figure 3 shows the HAIC prediction for just one forecast timestep, valid at the time that northbound flights would be reaching the higher risk area. However, work-to-date (Wang Ying, 2023) has shown that the nowcast skill drops away considerably after the first few hours, so it may be more accurate to produce a blended nowcast and NWP product for using this information on flight planning timescales. This is particularly pertinent for this LHR to JNB route as the convection over central Africa has a strong diurnal cycle which will not be captured by purely advection-based nowcast methods. Figure 3 demonstrates how it is possible to compare the possible exposure to HAIC along different flight routes and how this information could be used to not only select a route with lower exposure but also give more information about hazard avoidance (and as a crude example, whether it’s best to avoid the storm to the right or left).

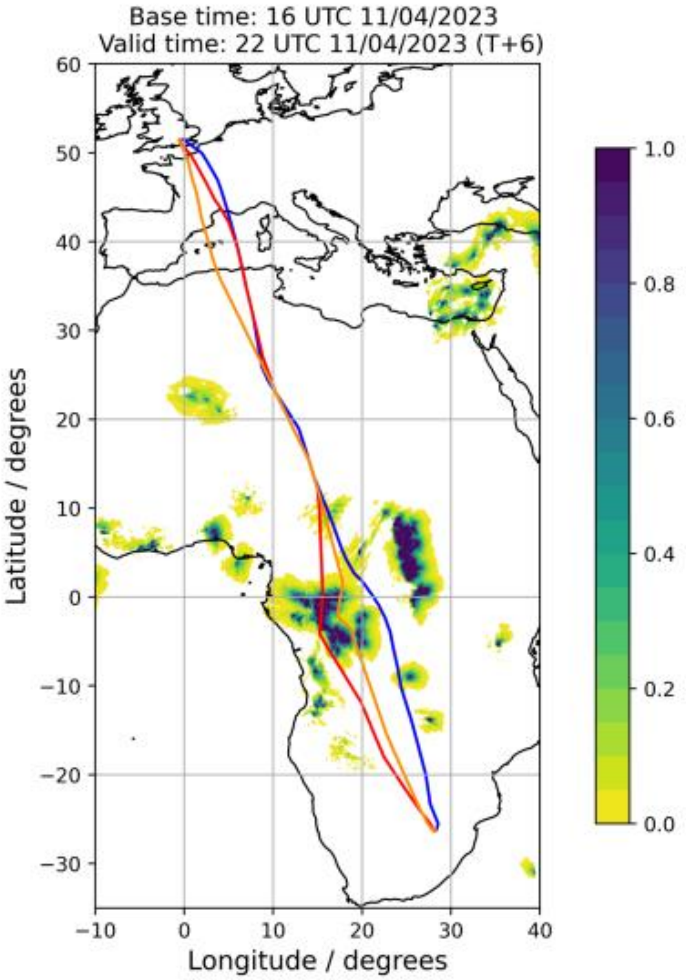


*Figure3: T+6 hour nowcast of HAIC likelihood, overlaid by three flight tracks between JNB and LHR.*

Global satellite-based products exist which would be most suitable to cover the entire JNB-LHR flight route. This includes products from EUMETSAT such as the Global Instability Index (GII) for the pre-storm environment as well as the global NWC SAF products for observations and nowcasts (Fig. 4). A full set of recommended products to explore for nowcasting along the LHR-JNB flight route appears in Sec. 3 of this report.

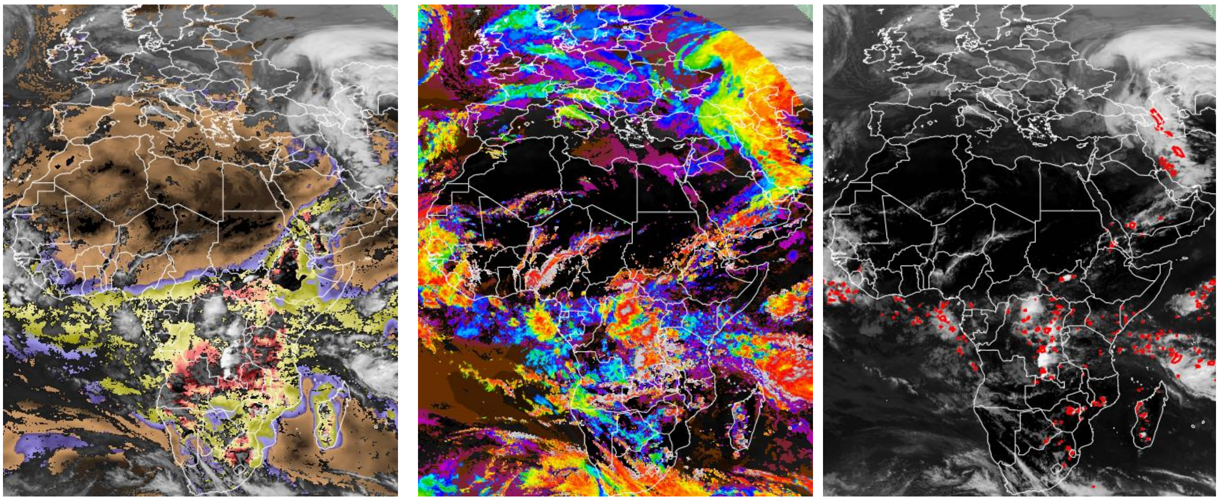


*Figure 4: Examples of global satellite-based products between JNB and LHR including GII (left), Cloud Top Height (centre) and RDT (right).*

## 2.2 HKG-SIN

### 2.2.1 Seamless blended forecast

### *2.2.1.a Convective weather nowcast*

The Hong Kong Observatory (HKO) has developed a suite of nowcasting systems, including the "Short-range Warning of Intense Rainstorms in Localized Systems" (SWIRLS), to aid rainstorm warning operation as well as high-impact weather forecasting for the public and the aviation community (Cheung et al. 2014; WMO, 2017; Woo et al., 2017). To extend the coverage of this nowcasting system (Leung et al., 2020; Chan et al., 2021), the HKO used artificial neural network (ANN) technique to simulate radar reflectivity from 7 spectral bands observed by the Advanced Himawari Imager (AHI) of the Japan Meteorological Agency (JMA) Himawari-8 (H-8) satellite. In addition, the ANN model was applied to observations by the GEO-KOMPSAT-2A (GK-2A) satellite of the Korea Meteorological Administration (KMA) to provide satellite derived radar reflectivity (SDRR) covering Central Asia and the Indian Ocean (Figure 5). The SDRR by H-8, now H-9, and GK-2A would be extrapolated at 30-minute intervals for up to 8 hours by a semi-Lagrangian scheme along the optical flow motion vectors.

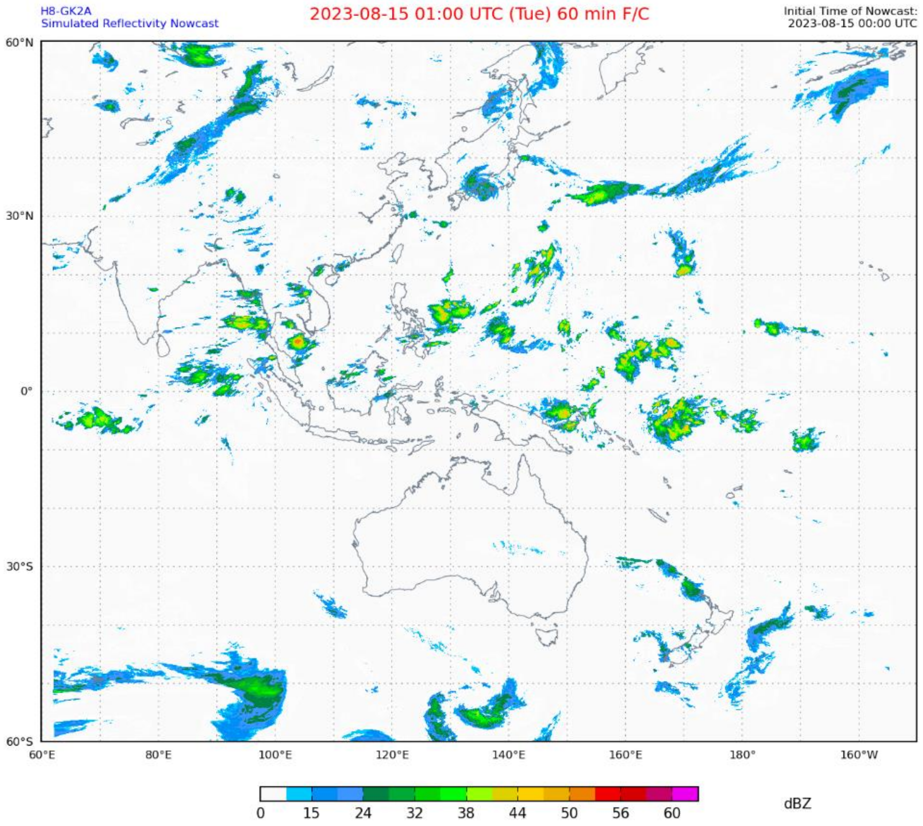


Figure 5. Example of SDRR extrapolated to T+1 hour.

### *2.2.1.b Regional numerical weather prediction (NWP) model*

HKO’s regional NWP, namely the HKO-WRF (Hon et al., 2020, see also https://www.hko.gov.hk/en/wservice/tsheet/nwp.htm) operates at a 10-km horizontal resolution with 42 vertical levels and runs 8 times a day using a three-dimensional variational (3DVAR) data assimilation scheme. The model takes the boundary conditions and initial fields from the National Centre for Environmental Prediction (NCEP) Global Forecast System (GFS) model at 0.25° resolution. Hourly precipitation from HKO-WRF was converted to radar reflectivity following a standard Marshall-Palmer (Marshall and Palmer, 1948) Z-R relation $Z=200R^{1.6}$.

### *2.2.1.c Blending technique*

With reference to "Rainstorm Analysis & Prediction Integrated Data-processing System" (RAPIDS) (Li et al., 2005) that blends outputs from SWIRLS with NWP to generate an optimal QPF for operational guidance in rainstorm situations, HKO developed blending technique based on extrapolated SDRR and NWP radar reflectivity (Cheung et al., 2023). At the development stage, weightings varying across latitudes and over tropical cyclone areas were explored. Based on fractional skill scores, optimal hourly weightings were chosen for T+1 hour to T+8 hours. Currently, optimal weightings were selected based on trailing 12-month's performance to provide hourly gridded information on the presence and distribution of convective weather for the next 8 hours. The forecast information could be 2D reflectivity or categorised into moderate/severe convection and will be updated every hour.

### 2.2.2 Hazardous weather encounter

To demonstrate the use of the forecast information for gate-to-gate avoidance of convective weather, an impact-based information called 'hazardous weather encounter' would be provided. Based on the latest hourly gridded forecast, information associated with the events of moderate/severe convection expected along a selected flight route would be calculated.

### *2.2.2.a Statistics*

The number of times and the associated duration of flight route crossing moderate/severe convection would be given. In addition, the number of times and the associated duration of flight route crossing valid SIGMETs would also be provided for users' reference.

### *2.2.2.b Avoidance metric*

After some discussions with local airlines, they have suggested HKO might try to quantify weather impact by the extra amount of deviation that might be required for pilot to fly around the convection. Considering the demonstrative cases below, the perpendicular distance from the planned flight route to the edge of the convection would be calculated (Figure 6).

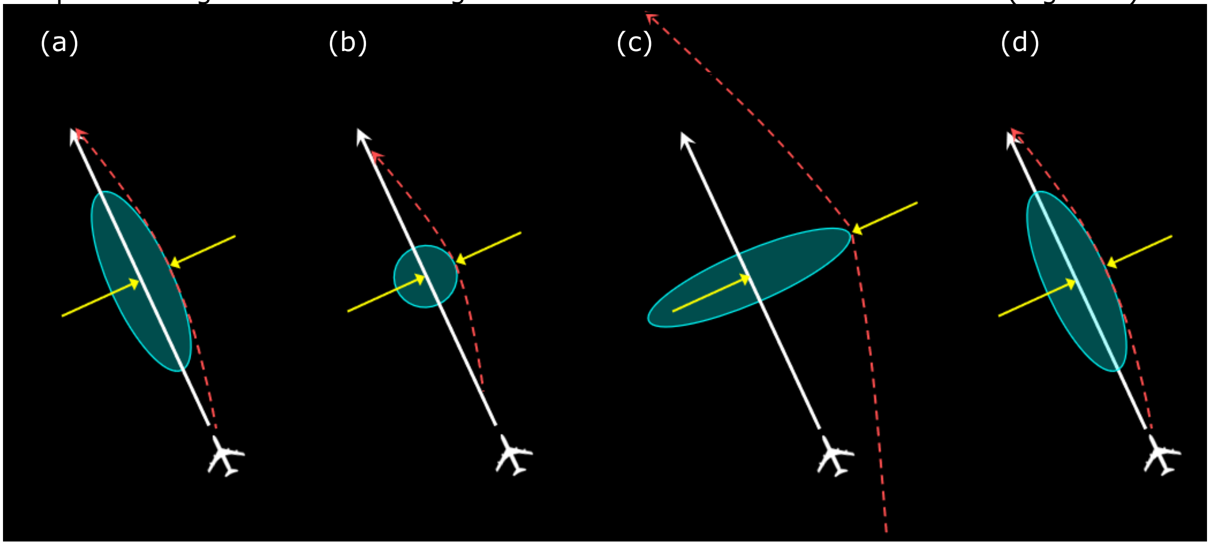
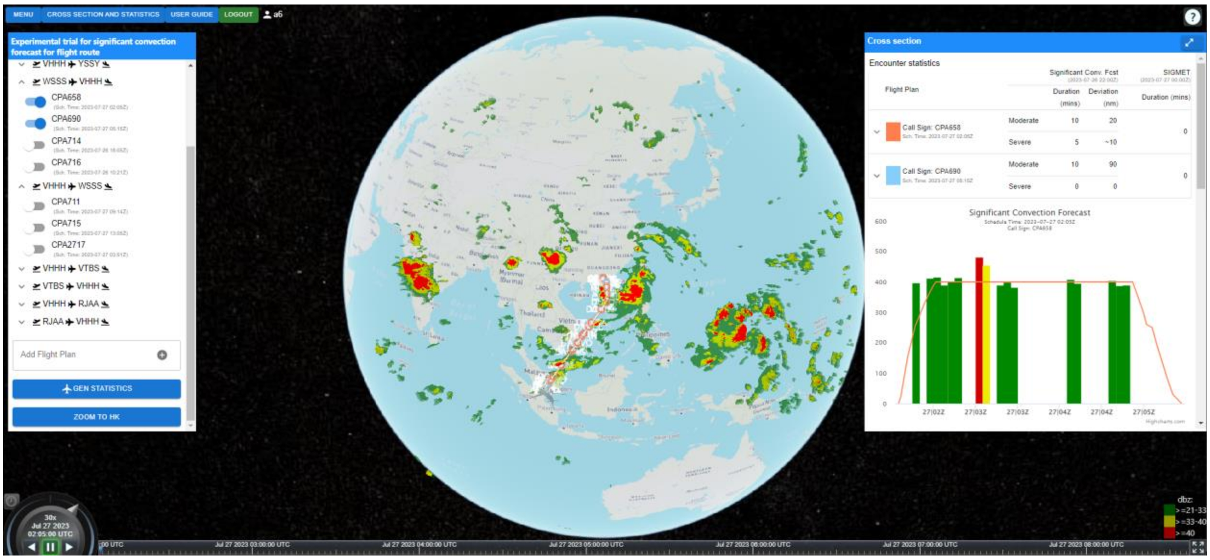


Figure 6. Although convective area (a) might be much larger than convective area (b), the amount of deviation required would be similar due to restriction of flight operation that sharp turns would be impossible. Even convective area (c) and (d) are the same, their orientation with reference to the flight route would lead to very different avoidance requirement. Therefore, the most simple but useful avoidance metric would be the distance bounded by the two yellow arrows respectively.

### 2.2.3 Web display platform

For visualisation and aiding stakeholders' decision-making process, a web-based interactive platform would provide an integrated view of MET and non-MET information, as well as retrieving the 'hazardous weather encounter' information (Figure 7).



| Flight Plan | | Significant Conv. Fcst (2023-07-26 22:00Z) Duration (mins) | Significant Conv. Fcst (2023-07-26 22:00Z) Deviation (nm) | SIGMET (2023-07-27 00:00Z) Duration (mins) |
|---|---|---|---|---|
| Call Sign: CPA658 | Moderate | 10 | 20 | 0 |
| | Severe | 5 | ~10 | |
| Call Sign: CPA690 | Moderate | 10 | 90 | 0 |
| | Severe | 0 | 0 | |

Figure 7. Web-based interactive platform providing an integrated view of MET information along selected flight route(s).

### 2.2.4 Blending with ensemble forecasts

A preliminary study was carried out to explore convective weather probability forecast for the Hong Kong – Singapore route. As mentioned in the previous progress report (September 2023), HKO blended convective weather nowcast and regional NWP model with optimal weighting selected based on trailing 12-month's performance. One way to access forecast uncertainty, or in this case convective weather probability, is to consider an ensemble forecast. The European Centre for Medium-Range Weather Forecasts (ECMWF) has pioneered a system to predict forecast confidence, namely the Ensemble Prediction System (EPS). It comprises one control forecast (CNTL) plus 50 forecasts each with slightly altered initial conditions and slightly altered model physics. The horizontal resolution of the 51 forecasts is around 9 km. The preliminary study looked into different ways to blend convective weather nowcast with each of the EPS forecast to produce a convective weather probability forecast.

Similar to the blended forecast, 3-hourly precipitation from ECMWF EPS was converted to radar reflectivity assuming uniform rainfall across the 3 hours and following a standard Marshall-Palmer (Marshall and Palmer, 1948) Z-R relation $Z=200R^{1.6}$. Optimal weightings used in blended forecast were not used in blending convective weather nowcast with ECMWF EPS as that would introduce too much weight of the convective weather nowcast at small forecast hours. This would then limit the capability of blended EPS forecast to quantify forecast uncertainty. Linear increasing weighting was used to conserve the higher forecast skill in convective weather nowcast at small forecast hours while allowing ECMWF EPS to provide forecast spread, especially in longer forecast hours.

Aligning with the convective weather definition used for blended forecast, convective weather probability is defined as the proportion of blended EPS giving a forecast of greater than 33 dBZ. Based on the convective weather probability forecast, the probability along the flight route can be generated similar to those available for the London-Johannesburg route (maximum probability, average probability and sum of non-zero probability). An extension to the existing product, i.e. spread in encounter duration and deviation distance, for the Hong Kong – Singapore route may also be produced based on the forecast spread.

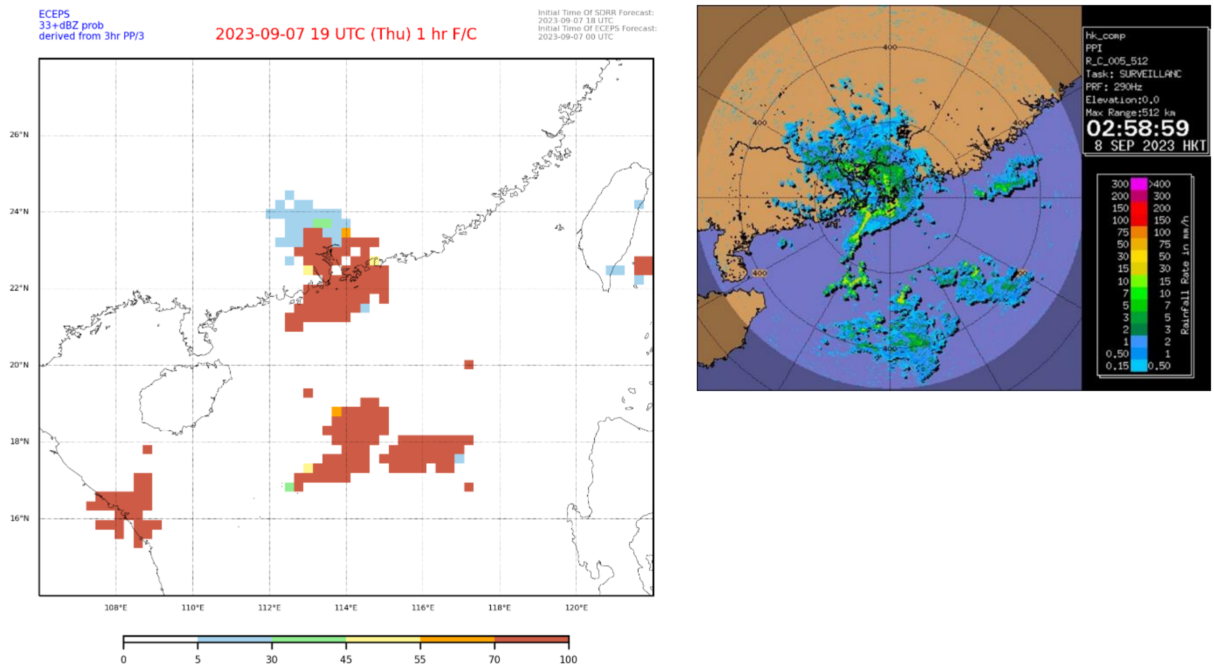


Figure 8. Example of convective weather probability at T+1 hour and actual RADAR observation. Left panel shows probability of 33 dBz in the column expressed as a percentile from the blended ensemble and nowcast information.

## 2.3 Convective Induced Turbulence

Aviation turbulence is a major source of weather-related aviation incidents, causing passengers and crew injuries and operational cost increases due to choosing non-optimal flying routes and occasional aircraft damage (Sharman & Trier, 2019; Storer et al., 2019a). Convection-induced turbulence (CIT) can occur within convective clouds but is also possible in clear air near clouds. While the in-cloud CIT can be mostly avoided using onboard radar and stationary satellite observations, the out-of-cloud CIT may be encountered by aircraft when they try to circumnavigate thunderstorms or sometimes accidentally fly into or over turbulent regions where the convection appears to be weak (Hamilton and Proctor 2003). Potential generation mechanisms for out-of-cloud CIT include 1) the enhancement of the background wind shear by convection penetrating into the upper troposphere, 2) cloud-induced deformation at the cloud boundary caused by buoyancy gradients, and 3) convectively generated gravity waves that propagate and break subsequently (Lane et al. 2003).

Forecasting tools for CIT and other types of aviation turbulence have been developed based on global weather model forecasts. Examples with global coverage include the Graphical Turbulence Guidance (GTG) algorithm (Muñoz-Esparza and Sharman 2018) and the global Korean deterministic aviation turbulence guidance (G-KTG) system (Lee et al. 2022). However, operational global weather models are known to have limited utility in predicting the location, intensity, and organization of convection because of their inadequate resolution and uncertainties associated with convection parameterization (Sharman et al. 2019).
Thanks to the advances in computing power, limited-area convection-permitting models have been successfully used in operational NWP in some regions (e.g., Seity et al., 2011; Tang et al., 2013; Depankar et al., 2020). More recently, global kilometer-scale resolution simulations have been experimented with (e.g., Wedi et al., 2020; Hohenegger et al. 2022) and suggest global NWPs at kilometer scales be promising in the medium-term future.

This CIT sub-project of AvRDP2 focuses on predicting aviation turbulence caused by convection. It contains four components briefly summarized below. Work has been conducted by a team at HKUST led by Xiaoming Shi. A postgraduate student, Mr. Haoming Chen, conducts most of the research work in this project at HKUST under the supervision of Xiaoming Shi and with help from the Hong Kong Observatory (HKO).

### 2.3.1 Predicting CIT with Convection-Permitting Simulations

This task aims to develop a new method to diagnose CIT intensity from convection-permitting (~1 km resolution) simulations. We developed a new method based on the scale-similarity principle that reconstructs sub filter-scale turbulence kinetic energy (TKE) and estimate eddy dissipation rate (EDR). This method has been applied to a few CIT cases and verified its skills. The work is described in Chen and Shi (2023a).

### 2.3.2 CIT Triggering Mechanism Due to the Interaction between a Jet Stream and Convection

This task aims to apply the EDR estimation method to a severe CIT case encountered by the Hawaii Airline near Hawaii in December 2022 and investigate the physical mechanism causing this incident. This study uses the Model for Prediction Across Scales (MPAS) to simulate the convective system in this case with 1-km resolution. It was found that during the incident, the mid-latitude jet stream intruded into low latitudes due to the formation of a low-pressure trough to the north of Hawaii. Near the jet exit region, a mesoscale convective system (MCS) developed around Hawaii. The MCS acted like an “obstacle” to the upper-level jet, which accelerated after passing this obstacle like a downslope windstorm passing over a mountain near the surface. This region downstream of the MCS in the upper troposphere had strong vertical shear, which created instability and turbulence (Chen and Shi, 2023b).

### 2.3.3 Probabilistic Prediction of CIT with Ensemble Simulations

This task is ongoing. A large ensemble forecast is needed due to the limited predictability and convective system’s sensitivity to initial conditions and model physics errors. Therefore, we need ensemble forecasts to encompass different evolution possibilities of a convective system. We have conducted large ensemble simulations for ten cases of severe CIT. We use three different physics parameters actions and ten different initial conditions for each case to obtain an ensemble of 30 members. Our current finding is that the unweighted average and calculation of turbulence probability work for some cases. Still, there are challenging cases in which most ensemble members fail to capture the incidences of turbulence. We experimented with elite selection algorithms, in which the ensemble member with cloud distribution resembling satellite observation is selected as the best prediction. It works well for cases where airplanes are cruising in the upper troposphere. Still, it performs poorly if the airplanes encounter turbulence during landing or taking-off in the lower troposphere.

### 2.3.4 Deep Learning-Based Nowcasting of Airport Turbulence

This task is done in collaboration with Dr. Pam Wai CHAN, the current director of the Hong Kong Observatory. It aims to forecast turbulence near the runways of Hong Kong International Airport (HKG). HKG has real-time LiDAR observation, which provides estimations of turbulence near the height of take-off and landing of airplanes. We are developing deep learning models that make predictions of turbulence intensity with a lead time of 15 min to 1 hour based on the LiDAR observation of the past hour. Haoming has finished preprocessing the LiDAR data and set up the software framework for training the machine learning models. Our current machine learning model’s skill is still relatively low because it fails to predict the generation of new turbulent areas. We will experiment with different model structures and combine the LiDAR observation with large-scale synoptic fields, which may provide critical information for the generation and decay of turbulence.

### 2.3.5 Deep Learning-Based Nowcasting of Fengyun-4A Satellite Image

This project is led by a postdoctoral researcher, Dr. Qiang ZHAI, affiliated with HKUST’s Electronic and Computer Engineering (ECE). Dr. ZHAI is jointly supervised by Prof. Xiaomeng LI from ECE and Prof. Xiaoming SHI. Dr. Zhai’s research focuses on deep learning-based nowcasting of the Fengyun satellite's image of clouds. This research is motivated by the need to use satellite images to assess the development of convection, which causes aviation hazards.

Currently, Qiang has finished preprocessing the satellite data, the raw data of which contains a significant fraction of missing or contaminated images. He has established the software framework to train and evaluate the deep learning models. However, our current deep-learning models suffer from the artificial smoothing of the predicted cloud images. Qiang is making substantial efforts to experiment with new deep learning model structures and enhance the deep learning model's skills. We expect a breakthrough in model performance in the next quarter.

## 3. AvRDP2: LOOKING AHEAD

### 3.1 LHR-JNB

For both the convection and HAIC examples above in section 2.1, this information could also be utilised from an alternative perspective, determining new route options that include hazard avoidance (as opposed to calculating the risk on existing flight plans). This has been demonstrated by Cheung (2018) where optimal flight routes are predicted using NWP winds and temperature, akin to what is used in commercial flight planning systems, but constraints are also included for hazard avoidance using different risk thresholds (which could be chosen by the customer). An example of this (using turbulence as the hazard) is shown in Figure 8.

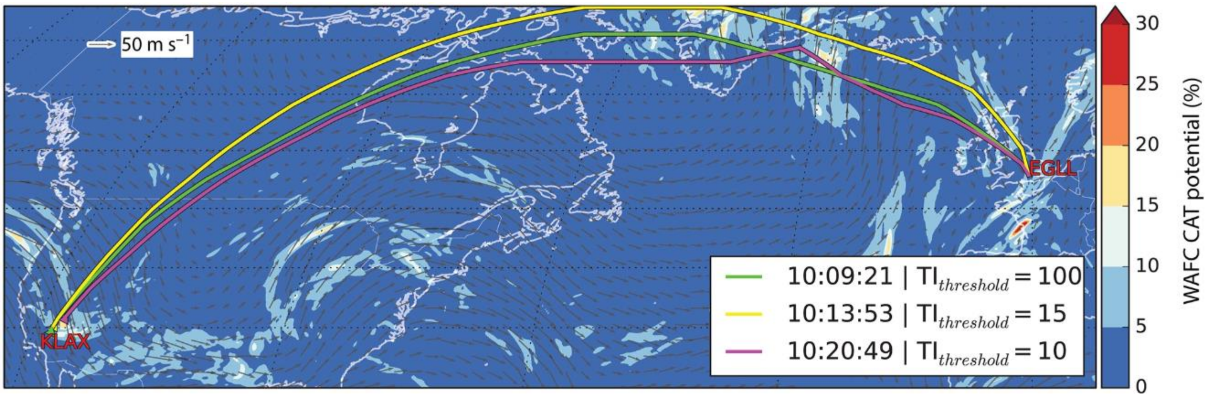


*Figure 8: Examples of trajectory prediction from London to Los Angeles, showing different routes with different risk thresholds for turbulence encounters.*

The hazard information used in the trajectory prediction could be provided by a probabilistic forecast of convection. These probabilities could be determined by a blend of different sources of data, for example making use of nowcast data at the early stages of flight and transitioning to purely NWP-based information en-route.

Due to the length of the LHR to JNB route, any nowcast information will only be used for the early stages of the flight, in and around the departure airport. Nowcasts would be very valuable en-route if uplinked to pilots' electronic flight bags, but this will not be feasible in the timelines of this project. Following are the nowcast products we propose to explore, in addition to the probabilistic WAFS data (and the reasons why).

- Met Office HAIC nowcast: There are currently very few readily available HAIC nowcasting products over this flight route area. There is a new capability within the RDT product that could be looked at further, but the Met Office product is already running routinely and has archived data available for exploring past case studies.
- NWC-SAF products: Both the UK Met Office and SAWS run local versions of the NWC-SAF. Several useful products exist within the NWC-SAF framework that can be utilized over this flight route, including RDT, precipitation estimates, and cloud top temperatures & heights for the detection and nowcasts up to 1 hour ahead. Satellite-based instability indices from the NWC-SAF iSHAI products (or GII products) can also

be considered to assess the pre-storm environment in order to forecast the potential for convection (e.g. > 2-hour lead-time), while NWC-SAF Convection Initiation (CI) products could also be considered. In order to cover the entire flight route, it is advisable to consider the Global NWC-SAF output to cover the entire flight route. Global NWC-SAF data can be ordered from EUMETSAT for the product as testing, and the possibility also exists to activate and obtain data operationally for implementation through the EUMETCast dissemination platform (e.g. in place at SAWS).

- High-resolution nowcasts: Both the UK Met Office and SAWS have radar systems covering the terminal area (taxi, take-off/landing, and ascent/decent phases of flights). High-resolution nowcasts from radar using TITAN to identify, track, and nowcast (up to 1-hour) can be considered in the project. This includes the detection of hazards such as hail, precipitation and wind gusts. Lightning observations and nowcasts can also be considered.

Although some verification analysis was done in the work to date, this focussed on the skill of the HAIC nowcast (with an imperfect truth dataset) and was carried out over only a few case studies. A challenge with HAIC is the lack of a 'truth' dataset to verify against. Although there is a satellite-based HAIC detection product available, this is used as an input to the nowcast and so would not be a fair measure. A more comprehensive verification strategy is required over a longer period of time and, if possible, using a consistent approach between the LHR to JNB and HKG to SIN airport pairs. This verification may be two-fold; verification in terms of assessing the skill of the meteorological hazard forecasts and a plan for how we measure the benefit of the work. Neighbourhood-based verification metrics such as the Fractions Skill Score (Roberts and Lean, 2008) will be useful to consider helping avoid the double penalty problem. The WAFS deterministic convection forecast could be used as the baseline global product to compare against, using overshooting top products from geostationary satellites as a global observational dataset.

User engagement will be key for the next stage of this work. The Met Office has initiated engagement with the forecasting team at NATS (the UK's national air traffic control service). More consideration needs to be given to how this information will be displayed and shared with the user, for example following a similar approach to that proposed for the HKG to SIN route.

## 3.2 HKG-SIN

After several online meetings between HKO and Meteorological Service Singapore (MSS), a joint participation plan has been drafted. There would also be data exchange between HKO and MSS for a more robust assessment on the impact of regional observations or forecasting capabilities to the blended forecast. MSS and HKO will engage its users respectively to demonstrate the use of the seamless MET information for their decision-making and planning. The assessment and validation results of the seamless MET information and its application in gate-to-gate avoidance of significant convection would be included in a joint report upon concluding the project.

The tentatively timeline is given in Table 9 below:

| **Period** | **Tasks** |
|---|---|
| By Q4 2023 | Confirmation of project plan<br>Invitation of users' participation |
| By April 2024 | Development of products |
| **April 2024** | **Commencement of the project** |
| April 2024 – Q1 2025 | Demonstration and trial of products |
| Q1/Q2 2024 – Q4 2025 | Validation and verification of products |
| Q3/Q4 2024 | Progress report (Tentative) |
| **Q2 – Q4 2025** | **Final report and recommendations** |

Table 9 Timeline for deliverables for the HKG-SIN convective products.

Work by HKUST will continue through 2024. Two ongoing tasks by Haoming CHEN aim to extend the research to end users. One task attempts to provide a probabilistic forecast of convectively induced turbulence. Although, a large ensemble of kilometre-scale resolution simulations may not become operational soon. Our EDR estimation and probability weighting methods may be applied to the 9-km ECMWF ensemble forecast with some calibration. The other research aims to forecast turbulence near the airport using machine learning and LiDAR observation.

A final ongoing project led by HKUST is the nowcasting of satellite images of clouds. We hope to combine machine learning and remote sensing to provide useful predictions of convection development. We will collaborate with HKO to connect the prediction with forecasters' experiences and metrics for estimating aviation hazards. We expect all the unfinished tasks to have breakthroughs in one or two quarters and submit the corresponding manuscripts within one year.

## 4. REFERENCES

1. Anderson, G., Creswick, A. and Buchanan P. (2023) Interim Report on Probabilistic Convective Cloud Forecast Development. Internal Met Office report.
2. Chan W.S., Leung C.Y.Y., Li P.W., Enhancement of the HKO Satellite Derived Radar Reflectivity Algorithm in Recognition of Significant Convection, The 34th Guangdong - Hong Kong - Macao Seminar on Meteorological Science and Technology and The 26th Guangdong - Hong Kong - Macao Meeting on Cooperation in Meteorological Operations, Macau 3-5 November 2021
3. Chen, H., and X Shi, 2023a: Predicting Convectively Induced Turbulence With Regionally Convection-Permitting Simulations, Mon Wea. Rev. Submitted.
4. Chen H., and X. Shi, 2023b: Aviation Turbulence Induced by the Interaction between a Jet Stream and Deep Convection, J. Geophys. Res., Submitted.
5. Cheung, J.C.H. (2018). Flight planning: node-based trajectory prediction and turbulence avoidance. Met. Apps, 25: 78-85. https://doi.org/10.1002/met.1671
6. Cheung, P., Li, P.W. and Wong, W.K., 2014, July. Blending of Extrapolated Radar Reflectivity with Simulated Reflectivity from NWP for a Seamless Significant Convection Forecast up to 6 Hours. In 17th Conference on Aviation, Range, and Aerospace Meteorology.
7. Cheung, O. P., Y.Y. Leung, Y.L. Ng, M.H. Kok, and S.T. Chan, 2023: Seamless Significant Convection Forecast for Aviation by Blending Satellite Nowcast with Numerical Weather Prediction, to-be-published.
8. Dipankar, A, Webster, S, Sun, X, et al. (2020) SINGV: A convective-scale weather forecast model for Singapore. Q J R Meteorol Soc., 146: 4131– 4146. https://doi.org/10.1002/qj.3895.
9. Dixon, M. and Wiener, G., 1993. TITAN: Thunderstorm Identification, Tracking, Analysis, and Nowcasting—A Radar-based Methodology. Journal of Atmospheric and Oceanic Technology 10(6) pp. 785-797. Available at: https://journals.ametsoc.org/view/journals/atot/10/6/1520-0426_1993_010_0785_ttitaa_2_0_co_2.xml
10. Gijben, M. and De Coning, E., 2017. Using satellite and lightning data to track rapidly developing thunderstorms in data sparse regions. Atmosphere, 8(4), p.67.
11. Hohenegger, C., Korn, P., Linardakis, L., Redler, R., Schnur, R., Adamidis, P., et al. (submitted) (2022) ICON-Sapphire: simulating the components of the Earth System and

their interactions at kilometer and subkilometer scales. In open review for Geoscientific Model Development.

12. Hon, K.-K., 2020: Tropical cyclone track prediction using a large-area WRF model at the Hong Kong Observatory. Tropical Cyclone Research and Review, 9 (1), 67–74.
13. Hong Kong Observatory: https://www.hko.gov.hk/en/wservice/tsheet/nwp.htm
14. Lee, D., Chun, H., Kim, S., Sharman, R. D., & Kim, J. (2022). Development and Evaluation of Global Korean Aviation Turbulence Forecast Systems Based on an Operational Numerical Weather Prediction Model and In Situ Flight Turbulence Observation Data, Weather and Forecasting, 37(3), 371-392.
15. Leung, C.Y.Y., Tam, H.C., Chan, W.S. and Fok, H.K., 2020, January. Development of Satellite-based cloud top height and convection nowcasting products in support of SIGMET Coordination in APAC Region. In 20th Conference on Aviation, Range, and Aerospace Meteorology, 16 Jan 2020.
16. Li, P.W., W.K. Wong and S.T. Lai, RAPIDS - A New Rainstorm Nowcasting System in Hong Kong, WMO/WWRP International Symposium on Nowcasting and Very-short-range Forecasting, Toulouse, France, 5-9 September 2005.
17. Marshall, J.S. and Palmer, W.M.K., 1948. The distribution of raindrops with size. Journal of Atmospheric Sciences, 5(4), pp.165-166.
18. Muñoz-Esparza, D., and R. Sharman, (2018) An improved algorithm for low-level turbulence forecasting. J. Appl. Meteor. Climatol., 57, 1249–1263, https://doi.org/10.1175/JAMC-D-17-0337.1.
19. Muñoz, C., Wang, L.-P., & Willems, P. 2018. Enhanced object-based tracking algorithm for convective rain storms and cells. Atmospheric Research, 201, 144–158. https://doi.org/10.1016/j.atmosres.2017.10.027
20. Roberts, N.M. and Lean, H.W. (2008). Scale-selective verification of rainfall accumulations from high resolution forecasts of convective events. Monthly Weather Review, 136, 78-97, 10.1175/2007MWR2123.1.
21. Rugg, A., Haggerty, J. and Protat, A. (2021). Global and Regional Patterns in High Ice Water Content Conditions. Journal of Applied Meteorology and Climatology 60(2) pp. 141-155.
22. Seity, Y., Brousseau, P., Malardel, S., Hello, G., Bénard, P., Bouttier, F., F., Lac, and Masson, V. (2011). The AROME-France convective-scale operational model. MonthlyWeather Review, 139(3), 976-991.
23. Sharman, R.D., Trier, S.B. (2019) Influences of Gravity Waves on Convectively Induced Turbulence (CIT): A Review. Pure Appl. Geophys. 176, 1923–1958. https://doi.org/10.1007/s00024-018-1849-2
24. Storer, L.N., Williams, P.D. & Gill, P.G. (2019a) Aviation Turbulence: Dynamics, Forecasting, and Response to Climate Change. Pure Appl. Geophys. 176, 2081–2095. https://doi.org/10.1007/s00024-018-1822-0
25. Tang, Y.M., Lean, H.W. and Bornemann, J. (2013) The benefits of the Met Office variable resolution NWP model for forecasting convection. Meteorological Applications, 20, 417–426.
26. Vertrees, V. (2023). Using Ensemble Weather Forecasts to Reduce the Risk of Aircraft Encountering Convection. A Master of Science dissertation in Applied Meteorology at the University of Reading, UK.
27. Wang Ying, Y. (2023). Time to fasten your seat belt? Using probabilistic information to reduce the risk of aircraft encountering high-altitude ice crystals. A Master of Science dissertation in Applied Meteorology at the University of Reading, UK.

28. Wedi, N. P., Polichtchouk, I., Dueben, P., Anantharaj, V. G., Bauer, P., Boussetta, S., et al. (2020). A baseline for global weather and climate simulations at 1 km resolution. Journal of Advances in Modeling Earth Systems, 12, e2020MS002192. https://doi.org/10.1029/2020MS002192

29. https://rsmc.hko.gov.hk or WMO Manual on the Global Data-Processing and Forecasting System (GDPFS) (WMO-No. 485, 2018)

30. Woo, W.C., Ip, Y.Y., Wong, W.K. and Chan, N.H., 2017, December. Development of Satellite Reflectivity Retrieval Technique for Tropical Cyclone Rainfall Nowcasting. In Fourth International Workshop on Tropical Cyclones Landfall Processes (IWTCLP-4) (pp. 5-7).