Aviation Research Development Project Phase 2 (AvRDP2)
Science Plan
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1. Project Definition

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."

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 probability levels and other assessments for the end-users), as well as on forecast verification and validation."

Scope: Gate-to-gate avoidance of convective hazards along selected flight routes

How: The Project is 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 would involve, for example, airport city-pairs to demonstrate the gate-to-gate use of advanced aviation meteorological information in the future aviation operations environment. It would require seamless meteorological information from ground-based operations, take-off, ascent, cruising, descent, until landing phase to support the safe and efficient flight operations for the whole trajectory. The Project fits well with WMO's seamless earth system initiative, where "seamless" refers not just to the time-scales 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 observations, including the benefits of additional observations for the purpose of verification.

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 inflight (tactical) and pre-flight (pre-tactical) decisions. The project will study 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 will be placed on the advancement of the use of ensemble techniques in probabilistic forecasting and statistical methods for assessing the uncertainty/ reliability of the information, as well as on verification and validation. There is also a need to link with the Seamless-Global Data Processing and Forecasting System (S-GDPFS) concerning data availability and future modelling improvements. Close connection with the aviation users via, e.g., SC-AVI under SERCOM, would be required to ensure the outcomes are fit-for-purpose.

Who: The Project will be conducted collaboratively involving scientists from national meteorological and hydrological services specifically those providing aeronautical meteorological-services, universities and research institutions, guided by a continuous and iterative consultation process with aviation stakeholders such as ICAO (representing regulators), IATA (airlines), IFALPA (pilots), ACI (airports), IFATCA (air traffic controllers), CANSO (air navigation service providers) and other relevant experts. This collaboration would be designed to facilitate better understanding of the impact (including "secondary impact") of meteorological hazards to aviation. This will ensure that the meteorological requirements for a range of decision-making horizons (time and space) and a range of aviation operations (airport, terminal area and en-route) remain central to the project.

Governance: It is proposed that the project be 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. RB will take charge of the research element while SERCOM and the community advisory group (CAG) will serve as the channel linking WMO with the International Civil Aviation Organization (ICAO) and other aviation stakeholders 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 Task Team involving relevant WWRP/WGs, Core Projects, as well as SC-AVI/ET-MHS from SERCOM is to be formed to guide and oversee the Project. SERCOM and INFCOM will jointly contribute to the operation aspects especially on the R2O aspect.

When: The Project is expected to last 5 years from 2021 -2025 with periodic reviews of progress to be conducted after an Initial phase (around early to mid-2021) and at the mid-point around late 2023. After 2023, the project will enter an operationalization phase focusing on R2O. A final review of the project will be conducted in late 2025.

WHY (supplementary): *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 for the flight planning phase and 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 "chart-centric" approach to a modern "data-centric" approach to MET service provision that is appropriate for risk management and other needs (e.g. visualisation) as articulated through ICAO's GANP and an ICAO 'White Paper' of 2018 titled 'Future Aeronautical Meteorological Information Service Delivery'. This project is intended to further scientific advancement, and apply the scientific findings and new methodologies to service delivery ('science-for-services') to demonstrate the achievable benefits to aviation users.*

2. R2O Considerations

2.1. Applying Research Outcomes of this project to Air Traffic Management

Air traffic management (ATM) is the dynamic, integrated management of air traffic and airspace including air traffic services (ATS), airspace management (ASM) and air traffic flow management (ATFM). In the AvRDP2, ATS, especially air traffic control (ATC), and ATFM would be targeted at as the users of meteorological information. ATC is a relatively tactical operation to control aircrafts in flight, and ATFM has more strategic aspects to manage the whole air traffic for the safety and efficiency. For the en-route operations, in the primary focus of this project, information is required to decide whether an aircraft can fly along its intended route or must deviate because of some hazard or concern.

As spatial information, the required meteorological elements will be the following:

- Presence of types of clouds to be avoided (severe convection in this project) and their distribution.
- Cloud top height.
- In addition, ATFM operations must determine whether a flight route or airspace is available or an alternate route is necessary. For this purpose, information must be spatially seamless along the whole route. Given that the radar coverage may be partial or absent on the route, satellite products would provide the observational backbone for this project.

As types of information, for example, the following methods are conceivable.

- Impact based information for air traffic on preset air routes.
- Information on distribution of convection areas that affect air traffic.

Concerning the temporal aspects of the information, the required lead time for information provision is different, because ATC is a tactical operation targeting near real time, and ATFM is a more strategic operation.

- For ATC, real time and nowcast information will be effective. For example, when changing the runway to be used due to a change in wind direction in the terminal area, it is said that information about 30 minutes in advance is required. A similar lead time, perhaps up to an hour, would be required to avoid convective hazards in the terminal area.
- For ATFM, forecast information with a lead time of flight time plus 2 hours will be required, and nowcast information would also in some situations. For example, there is a method of coping with adverse weather at the airport or airspace by adjusting the departure time from the airport. Since the adjusted departure time is decided several hours before the Off-Block Time, it is necessary to anticipate the flight time plus 2 hours or more as a lead time for adverse weather forecasts. In addition, there are also more tactical ATFM methods, especially in domestic ATFM, so there are situations where nowcast is effective.

The combined tactical and strategic requirements imply that a system based on both numerical weather forecasts (strategic), observations (tactical), as well as a blend of extrapolated observations and numerical forecasts, will be needed for seamless information.

2.2. Obtaining feedback from users to understand benefits of hazard data sources

Feedback from aviation users can help scientists and researchers better understand their requirements during the initial phase, and to validate that the products developed and demonstrated are indeed fit-for-purpose in the operationalization phase. To get feedback, one or more of the following tools could be deployed:

- Direct interview of the targeted users or agreed players on a demonstration.
- Realtime / Near-realtime feedback collect routinely if a parallel run and/or intense operation trial could be conducted for a period of time for a demonstration.
- Simulated environment created for selected representative cases to assess the usefulness of additional information when it is incorporated into the operation workflow during playback of these cases.
- Questionnaires for a group of users to profile their views.
- Polling performed on a group of similar users for obtaining preferences.

Though collectively called the aviation users, different user groups have diverging needs arising from unique business pain points, which can result in different concerns for a particular spatial and temporal scale of convection. For example, an airlines dispatch office does flight path planning and falls into the pre-tactical time frame. It strives to balance between safety and operation cost (crew time, fuel burn, fleet utilisation, etc.) and formulates its decisions based on the entire flight path. On the other hand, air traffic control concerns primarily tactical decisions regarding how convection would affect the busiest airway(s) in their area of responsibility (flight information region), a segment or segments where many flight routes overlap. That said, these requirements can crossover for dispatch offices when providing flight following service, or for air traffic service unit when implementing flow control measures. It is therefore important to remain specific on the use cases and scenarios when collecting user feedback. Benefits may be expressed in terms of flight time/distance, fuel burn, payload, orderly of traffic, capacity of air space, smoothness in operation, preparedness for flow constraints, advanced flow management, etc. Therefore, questions for users on benefits, or lack thereof, of a particular hazard information source should best reflect improvement or not in these metrics.

AvRDP2 has formed a Community Advisory Group (CAG), with a mixture of aviation experts from different sectors, to periodically engage with scientists and product developers as the project progresses. The intent is to provide iterative feedback from the CAG, who also will connect with others in the user community, so that products developed are most likely to meet user needs.

3. Proposed Investigations

The project proposes to focus on two timescales on which aviation users make decisions, as outlined in the preceding sections.

i) Tactical re-routing for pilots – observation/nowcasting (0-2 hours forecast lead time)

ii) Flight planning - probabilistic information (up to 24 hour forecast lead time).

Any tools that are developed and/or investigated as part of this project for these two use cases should be tested according to the framework of useful, usable and used. The aim for each tool will be to get as close to all three as is possible. However, it is not suggested an idea is discounted because, for example, it is only likely to be associated with the first row of table 1 (i.e. 'Useful') because technology and science are evolving all the time so products and services can be produced in increasingly quicker and more flexible ways. Furthermore, the finite duration of AvRDP-2 (through 2025) implies that the majority of the effort will be on the first two rows of Table 1. Thorough trial and evaluation of operational products will await official implementation into the operational product stream and proper evaluation, which may require several years.

Useful	Tool is of interest in principle to solve a real life problem.
Usable	Tool is available to users at the right time in the right format and is possible to use it in real time.
Used	Tool is used in practice (over say a year or multiple days at least) and does improve the customer's decision making. It's trusted by its users.

Table 1 Explanation of useful, usable and used.

3.1. Tactical Tools for En-Route Decision Making

Once a plane is en-route, convective weather is handled by tactically avoiding the areas of hazardous weather. Typically, detection is achieved via the onboard radar which gives a lead time of around 10-15 minutes. To enhance the lead time for detection, it would be useful to make products derived from geostationary satellites as the global 'baseline' with potential to bring in additional local or regional capabilities to add value e.g. around terminal areas. Nowcasting, building from the global baseline, would bring much more capability. On time ranges as short as 1-2 hours, nowcasting approaches can be used to estimate the locations of significant deep convection and their likely evolution within the predictability lifetime of the larger convective storms. Due to the spin-up of convection permitting models from the analysed initial conditions, the first 1-2 hours of NWP forecasts are not useable on their own and nowcasting relies heavily on high resolution observations (spatially and temporally) and forms of statistical extrapolation. Given that advanced high-resolution data assimilation of geostationary cloud information into NWP models is still an active area of research, in this project, we anticipate that 'tactical decisions' taken by pilots (with help from ATC and airline support) to avoid convective hazards will be primarily informed by improved nowcasting information – given the short time-range.

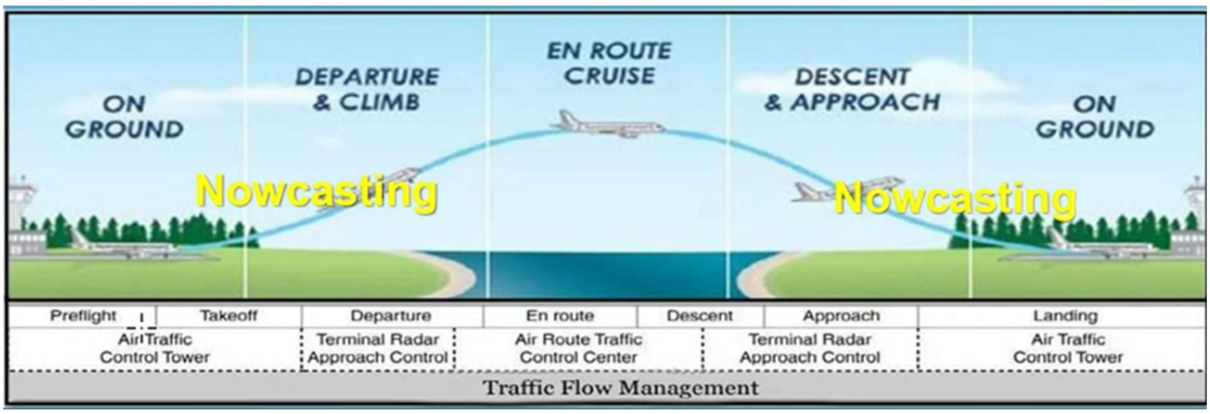

Figure 1 Schematic of in-flight convective information sources for the tactical forecasting case.

3.2. Probabilistic Numerical Weather Prediction (NWP) weather information for Fight Planning.

In contrast to tactical decision making (made en-route and described more previously), flight planning operations, either by pilots with airline dispatch or in air traffic management by ATC centres, require a much longer lead time. For example, the pilots must file their flight plan 1.5-2 hours before take-off and consider the potential hazards in the vicinity of the departure airport, enroute and at the destination airport. Given long-haul flights of 12 hours or more and the latency of NWP forecasts (the time between initialisation and the time that the forecast is issued) it would be typical to use the most recent forecast data with lead times of 12-18 hours. With many global model forecast products only available after 6 hours that makes the age of the observations used in the forecasts up to 24 hours.

As lead time increases this would be best informed by a blend from nowcasts with NWP forecasts, with ensemble information becoming increasingly important with lead time.

The exact nature of decision tools developed during this project will become clearer as the project progresses but it is anticipated that the products will include:

i) General weather products for the whole route. (Likely a cross section view of winds and indications of areas of severe convection.)

ii) Suggestions of different routes based on potential hazards / fuel consumption (efficiency)

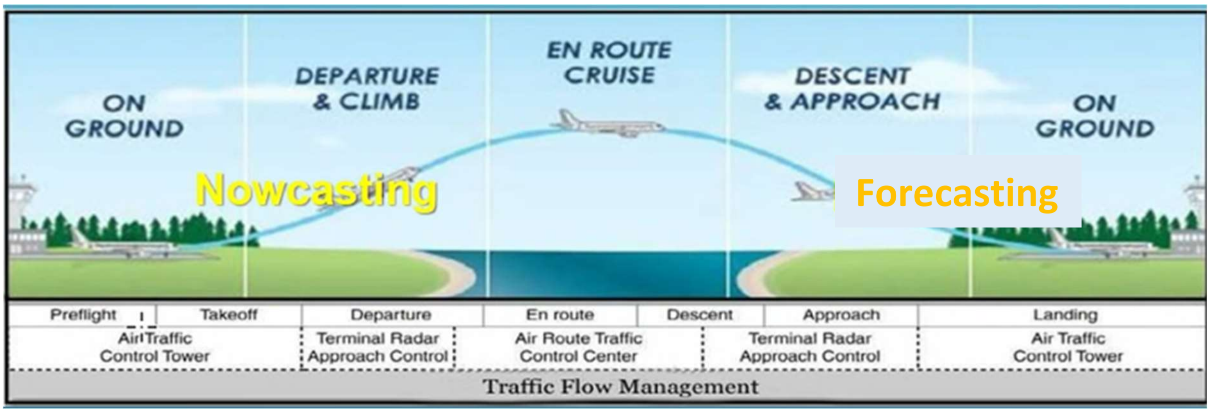

Figure 2 Schematic of inflight information sources.

4. Connection to the ICAO Hazardous Weather Information Service (HWIS).

The two use cases for this AvRDP2 project described above cover forecast lead times from 0 to 24 hours. This overlaps with the lead times for the HWIS project. Hence, this section covers the link between these two projects.

At the Meteorology Divisional meeting in July 2014, the International Civil Aviation Organization (ICAO) acknowledged the long-standing issues with the provision of en-route hazardous weather information (SIGMET), the main one being inconsistencies at flight information region boundaries, and the non-issuance of SIGMETs by some Meteorological Watch Offices (MWOs), with the potential negative impact on flight safety and efficiency. [Note, the ICAO Meteorology Divisional meeting was convened conjointly with the fifteenth session of the WMO Commission for Aeronautical Meteorology (CAeM-15).] ICAO urged Members States to consider possible options to address the issues highlighted. As a consequence of the Divisional meeting and after having discussed an initial solution based on regional centres who would support MWOs for the provision of more harmonised SIGMETs, the ICAO Meteorology Panel (METP), with the assistance of WMO, has agreed to pursue a new concept under the auspices of the Hazardous Weather Information Service (HWIS).

The purpose of HWIS is to provide globally consistent (seamless) information on weather and other environmental phenomena that pose a risk to aviation en-route operations: convection, icing, turbulence, dust and sandstorm, volcanic ash, tropical cyclone. HWIS includes inputs from global, regional and local providers. One critical (and key-for-success) point of the HWIS concept is the blending of several sources of input data. Moreover, its time horizon ranges from the observation (analysis) time to the next 4-6 hours. It aims at providing the best available observation, nowcast and forecast information to users, supporting all flight phases including pre-flight planning and in-flight re-planning. An ICAO METP working group addressing the HWIS concept has developed, with the assistance of WMO, a strategy for initial operating capabilities and considered several options for input data requirements and characteristics of output datasets.

As far as convection is concerned, the ICAO METP working group addressing the HWIS is currently developing an initial operating global capability for the detection of significant Cumulonimbus clouds, based on satellite imagery and other potential sources of observational data.

At the fifth ICAO METP meeting in June 2021, WMO reaffirmed the support of the meteorological research community to the development of HWIS, in the form of demonstrating the convection component of the HWIS concept through the second phase of the Aviation Research and Development Project (AvRDP2).

5. Research Topics Salient to AvRDP2

5.1. Introduction

Due to the size of this project it's not going to be possible to investigate every possible flight route around the world. However, through a series of discussions between the science steering committee (SSC) and the community advisory group (CAG) a range of possible flight routes was identified that covered some of the key aviation convection forecasting and nowcasting challenges namely to cover:

- (ideally) all 6 WMO regions and flights between regions.
- areas prone to convection and relatively remote regions.
- areas crossing the tropics.
- areas susceptible to HAIC over the ITCZ remains a concern.
- convection over continents (e.g. equatorial Africa or South America)
- short haul flights that have convection at the beginning, during and the end of the flight as a major risk, and for which there is some hope of predicting this convection prior to takeoff.
- (ideally) flights crossing the Pacific Ocean.

Figure 3 shows 8 flight routes that would cover these challenges. Although 8 flight routes sounds like a large number of routes some of the airports have multiple destinations which lowers the number of possible collaboration partners required to make this a successful research demonstration project. Even so, given the large number of collaborators and commitment required, the project will focus initially on two routes and aim to cover as many of the other routes as possible. The two routes are:

i) Hong Kong to Singapore (short haul: 3 hours 45 minutes)

   This route is prone to convection at all times of the year and along the entire route. Usually flights are tactically re-routed to avoid the areas of the most severe convection.

In the case of a particularly strong convection day the plane route will be adjusted to take into account this or even the plane may be delayed before taking off to save fuel and keep Air Traffic Control (ATC) workload at a reasonable level.

ii) London to Johannesburg (long haul > 11 hours)

This route has several distinct forecasting challenges owing to its length and also the variety of land /sea scapes it covers. Europe has its greatest convection challenges during May-July. . South Africa, being in the southern hemisphere, has its greatest convection challenges in October to March. Between these two areas, the Equatorial African regions have challenges due to scarcity of observations and year round convective weather events, many of which feature large, intense convective systems.

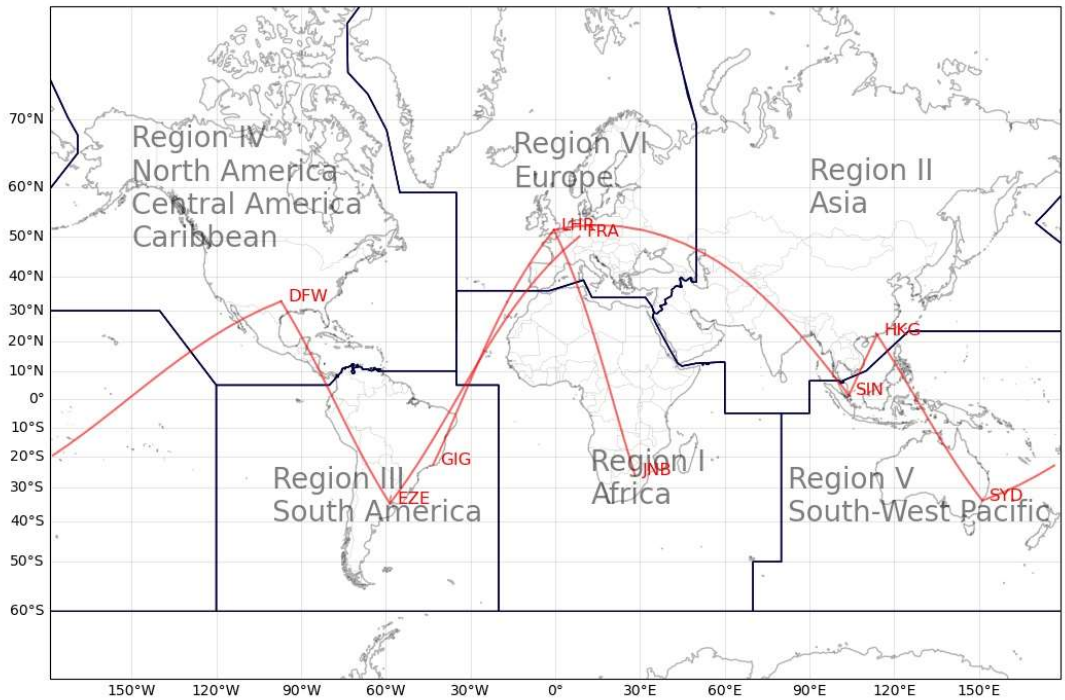

Figure 3 Potential flight routes for the AvRDP2 project.

5.2. Convection processes

Deep, moist convection in the atmosphere occurs in many forms, with organization on many length scales ranging from individual cumulus cells to mesoscale convective systems and tropical cyclones. Of interest to this project is deep convection that produces aviation hazards such as turbulence and high concentrations of ice crystals at flight level, as well as convection that interferes with takeoff and landing. While convection on the scale of individual thunderstorm cells can be disruptive, isolated cells are relatively easy for aircraft to avoid using on-board radar (except in the terminal area). More problematic are large areas of strong convection.

A climatology of "wide convective cores" (WCCs, Houze et al., 2015) shows where larger-scale convective storms tend to occur (Figure 4). Here, WCCs are defined as those contiguous 3-D convective echo objects exceeding a reflectivity of 30 dBZ over an area of at least 800 km2. We can see that there is a frequent occurrence of WCCs over tropical continental regions as well as portions of the Intertropical Convergence Zone over the oceans. Thus, a focus of AvRDP-2 is on flight routes that intersect these areas of relatively frequent occurrence of the larger convective systems.

Specific to the flight routes considered by AvRDP2, WCCs are prevalent along the LHR-JNB route across Africa, LHR-HKG across the Bay of Bengal and other areas in the Asian summer monsoon, DFW (USA) to EZE (Buenos Aires) in all months, as well as a broad summertime occurrence near Buenos Aires affecting all flights in that area. We also see significant disruptions possible for the flight routes connecting to Sydney, Australia, both from the Maritime Continent (HKG-SYD) and the South Pacific Convergence Zone (DFW-SYD). Finally, we note that the route HKG-SIN (Singapore) is entirely within an envelope of frequent WCCs curing the Asian summer monsoon, but the terminal area near Singapore is affected year-round.

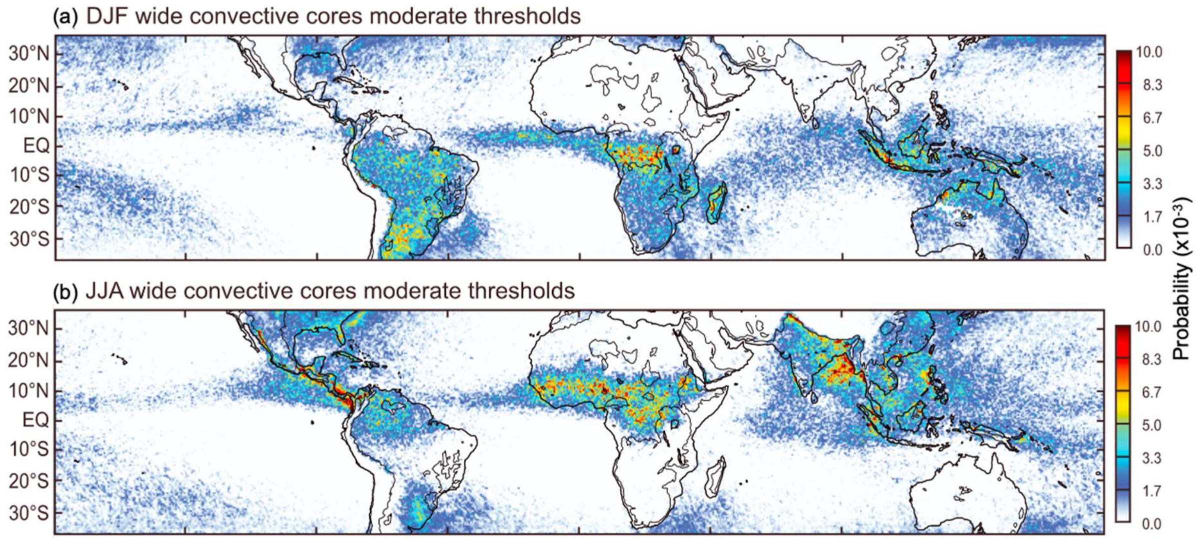

Figure 4 Wide convective core climatology for (a) December, January and February, and (b) June, July and August for the period 1997-2014 from the Tropical Rainfall Measuring Mission (TRMM) satellite. (adapted from Houze et al., 2015).

The primary interest in AvRDP-2 is predicting where deep moist convection will occur that gives rise to different aviation hazards. The predictability of such convection is limited to only an hour or so, at most, for individual thunderstorms. For clusters of storms that occupy areas of many tens to hundreds of kilometers, there is often greater confidence in prediction out to a few hours lead time, and occasionally longer, especially after the system has formed. Thus, focusing on the larger systems not only addresses the greater aviation hazard but also may lead to more effective prediction strategies.

5.3. Convectively Induced Turbulence (CIT)

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 (Sharman and Pearson 2017; 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.

Thinking about the potential benefits of existing regional and future global convection-permitting NWPs, the current project will tackle the following knowledge gaps for the prediction of CIT:

i) <u>Estimating the intensity of CIT relevant to aviation with the convection-permitting resolution NWP data.</u>
The turbulence scale relevant to most aircraft is on the order of 100 m. Therefore, kilometer-scale grid spacing still does not explicitly resolve the eddies relevant to aviation turbulence, though deep convection is acceptably resolved. Therefore a methodology to estimate the intensity of aviation turbulence, measured by the eddy dissipation rate (EDR), is needed. Existing methods developed for coarser resolution NWP data (e.g. Kim et al., 2021) could be modified for this purpose, or the Project can look into methods developed for gray-zone turbulence parameterization (Chow et al., 2019).

ii) <u>Efficiently utilizing ensemble NWPs for different time horizons and spatial scales.</u>
It has been demonstrated that the ensemble approach is beneficial for the prediction of aviation turbulence (Gill and Buchanan, 2014; Storer et al., 2019b). The issues of probabilistic forecasting are discussed below. However, besides those questions, additional considerations need to be given to the short-term forecast needs at the time scale of one to two hours. Relatively high accuracy is often expected for such a short lead time. Relying on a high-resolution ensemble alone may not deliver the accuracy needed by users. Combining satellite and radar data with NWP output may yield better forecast quality than using either source alone. Simple strategies include weight ensemble members based on observation (Raynaud et al., 2015; Kikuchi et al., 2018). Meanwhile, deep learning is a potentially powerful approach to using multiple sources to generate a hybrid forecast product (Espeholt et al., 2021).

iii) <u>Enhancing remote sensing products with the help of a large amount of ensemble NWP data.</u>
An unmentioned issue of the question and research direction above is that we do not have a large amount of truth data for turbulence. Therefore, the potential combination of remote

sensing and NWP data using deep learning, without additional steps, can only predict the satellite or radar images for the next few hours, for which we have a sufficient amount of data for deep learning. However, high-resolution NWP simulations can serve as a digital twin (Bauer et al., 2021) for the real atmosphere, and in this digital twin world, we know exactly the relationship between cloud distribution and turbulence. Therefore, when a large amount of high-resolution NWP data is available, they can be used for training a deep learning model to infer CIT intensity based on clouds. Then satellite and radar observation or nowcasting products may be used to give the CIT distribution in and out of clouds. The caveats are there are probably some degrees of errors in the relationship between clouds and turbulence in the NWP data and the tools for simulating satellite radiance (e.g. RTTOV) or radar reflectivity from model data are not perfect either.

Given that running global kilometer-scale resolution simulations is still computationally prohibitive when many runs are wanted, our project can only use regional or variable-resolution weather models to address the questions above.

5.4. High Altitude Ice Crystals

There has been a connection made between a number of jet engine power loss and damage events and the ingestion of ice crystals. Airlines have adopted a number of approaches to avoid these conditions ranging from the total avoidance of Cb clouds for some to tactical re-routing using real time satellite imagery. On-board weather radar typically does not identify these regions owing to the small size of the crystals. It's not a problem that affects the terminal area routing as it is restricted to high altitudes and moreover only affects certain parts of the world (Rugg et al., 2021). See Figure 5 (from Rugg et al., 2021):

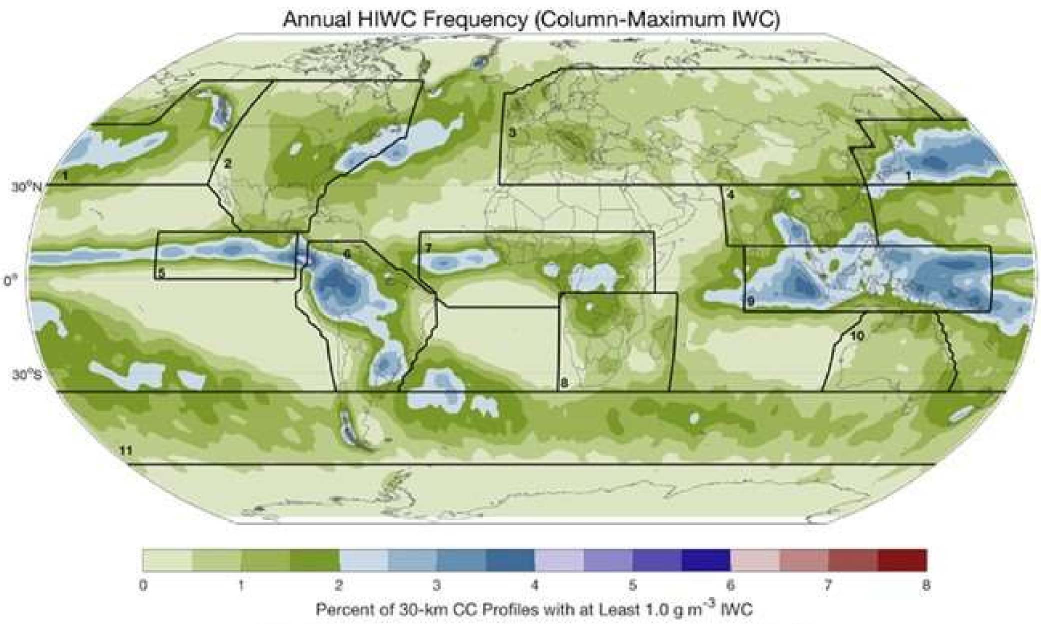

Figure 5 Annual HIWC (or HAIC) Frequency (Column Maximum IWC) (from Rugg et al., 2021).

Typical products for indicating areas prone to HAIC (or HIWC) split between satellite, nowcasting and NWP based (Haggerty *et al.*, 2019). One of the key questions in this field is the relative merit of these 3 types of products and also, in the case of satellite products about how well they work at night when less detection channels are available.

5.5. Probabilistic forecasting

Probabilistic forecasting is an essential input to risk-based decision making. The aim is to predict the uncertainty in the atmospheric state, including weather hazards, and also variables that are dependent on the atmospheric state (for example, flight duration or fuel burn). In numerical weather prediction models, there is a distinction between atmospheric phenomena resolved by the model dynamical core and unresolved processes (often described as "sub-grid scale"). The AvRDP2 project focuses on aviation hazards associated with deep convection – a phenomenon that is partially resolved in regional high resolution "convection-permitting (CP) models" and poorly resolved in even the highest resolution global models. Therefore, deep convection is a major challenge to NWP, especially in the tropics where it dominates high impact weather. In addition, deep convection arises from instability and evolves rapidly with typical predictability timescales for individual updrafts as short as 1-3 hours.

Recent pilot studies running CP ensembles in the equatorial region, including Southeast Asia (Ferrett *et al*, 2021) and East Africa (Cafaro *et al*, 2021) have demonstrated that there is skill in the prediction of heavy precipitation resulting from convection. The skill relies on probabilistic prediction – for example, forecasting the probability of precipitation above threshold over some neighbourhood of the location of interest. The range of useful prediction depends strongly on the geographical location, the large-scale flow situation, the scale of the neighbourhood examined and the model used. In the tropics there is enhanced predictability on scales greater than 200 km associated with equatorial waves that propagate both eastwards and westwards near the equator and also African easterly waves. Therefore, there is a sound scientific basis in prediction of convective weather systems if a probabilistic framework is used where the risk of events within a neighbourhood is the forecast quantity. The scale of the smallest neighbourhood with forecast skill is expected to increase as lead time increases and this behaviour can be quantified.

In terms of aviation forecasting, the project will consider three types of probabilistic forecast:

i) <u>The probability of events associated with unresolved processes.</u> In particular, HAIC and aviation turbulence (Haggerty *et al.*, 2019 and Storer *et al*, 2020) including turbulence associated with intense convection. The risk associated can be estimated using physical parametrizations driven by input from the resolved variables of the NWP model (either online while the model runs or offline after NWP is complete). This type of uncertainty can be estimated partially using a single "deterministic" model run, or more completely taking the large-scale uncertainty into account using an ensemble of NWP forecasts.

ii) <u>The probability of events that are partially or fully resolved in an NWP model.</u> Notably this includes the occurrence of deep convection, its intensity and precipitation rate. Some form of ensemble forecast is needed to do this, and there are a range of approaches including using global model ensembles, convective permitting (CP) ensembles over limited area domains and also lagged and multi-model ensembles created by combining a number of forecasts.

iii) Representing the uncertainty in the resolved flow and its impact on calculations relevant to aviation. An NWP ensemble is used to simulate a range of possible atmospheric states, including the horizontal wind components, temperature and pressure on many model levels and this data is used in multiple calculations. Examples include Trajectory Based Operations (TBO) where the flight time and fuel burn (e.g., Wells *et al*, 2021) between two airports can be optimised over a set of possible routings – these calculations depend on the wind and temperature integrated along the paths. The risk of hazards (e.g., turbulence, HAIC) along a set of potential trajectories can also be estimated numerically and then fed into a risk-based decision making tool where each trajectory can be assigned a risk (Prata *et al*, 2019, Cheung, 2018) and this is used to decide the best route. Recent research has led to the development of such a tool (V-DART) relating to routing around volcanic ash plumes (Harvey *et al*, 2022). The tool is being translated into operations with the London VACC scheduled for the end of 2025.

5.6. Machine Learning (ML) methods

Since the beginning of the 21st century Artificial Intelligence (AI) has gained much attention due to the emergence of big data and available processing power from supercomputers (Bochenek & Ustrnul, 2022). AI has shown great potential for many different application areas (Bonavita *et al* 2020) with Machine Learning (ML) the most widely used AI technique applied to the atmospheric sciences (Bochenek & Ustrnul, 2022). ML algorithms utilize data from one or more sources as input predictors to model a specific hazard output or predictand. This is achieved by identifying patterns in the datasets and relating those patterns with the predictand being modeled. ML is appropriate for the development of algorithms to link observations and/or NWP output to hazards that are not described well by current observational sources or modelled by NWP systems (Gagne *et al*, 2017).

Tactical decision-making of for convective hazards occurring over next 2 hours relies heavily on nowcasting where observations are advected forward in timeML is well-suited to link observations and NWP output with aviation hazards for both the tactical decision and flight planning phases of flight and may also be appropriate for determining the impact convection-related hazards may have on operations such as flight delays, re-routing, and fuel burn.

In the AvRDP2 project it is envisaged that ML methods may be investigated in the following 3 areas:

i) The identification of convective elements that pose a hazard to aviation. This includes new/enhanced algorithms to identify hazardous elements such as hail, lightning, rainfall, wind, turbulence, and HAIC (e.g, Mizuno *et al*, 2022; Haggerty *et al*, 2020). ML can be used to train models for pattern recognition and multi-parameter information extraction to detect aviation hazards from observational datasets, NWP, or a combination thereof.

ii) The development of new/enhanced methods to improve short-range forecasts of convection and associated hazards. ML techniques have the potential to improve the accuracy of traditional nowcasting methods such as extrapolation methods (Su *et al.*, 2020) or the blending of multi-parameter information from observations and NWP. ML can also be used for many applications to improve short-range forecasts, including blending nowcasts with NWP forecasts, extracting information from NWP forecasts, automatic detection of hazards from NWP output, post-processing, ensemble processing, statistical downscaling, and emulation of model components such as parameterization schemes (Bonavita *et al* 2020).

iii) Predicting the impact convective weather elements will have on flight operations. Apart from safety concerns, convection and associate hazards may result in significant disruptions to operations in both the en-route and terminal area. ML techniques can be utilised to link hazards with impact to translate the science into aviation impact.

5.7. Verification methods

Verifying forecasts is central in determining the accuracy and understanding of the errors to improve a forecasting system or any associated downstream products, e.g. hazard forecasts for aviation. It has been shown that diagnostic verification of both the meteorological input and the hazard forecast is valuable in isolating the influence of the weather forecasts' quality on the downstream product. The meteorological errors can include but are not limited to the hazard forecast's timing, spatial and magnitude, which can, for example, be caused by errors in NWP processes simulating convection.

With the introduction of ensemble forecasts to flight planning, evaluating the benefits of probabilistic convection forecasts, methods to verify high-resolution ensemble forecasts, and best use of probability forecasts are to be considered. The likelihood of convection occurring along the planned flight path is highly relevant to operational decisions made by airlines, so quantifying the uncertainty in the prediction of convection provides additional information to assist in determining associated risks in the planning process. A meaningful, seamless verification approach to the nowcast and short-range time scales must be applicable and give consistent forecast performance information for deterministic and probabilistic forecasts.

The proposed airport pairs represent a range of forecast lead times due to the duration of planning and tactical phases in trajectory based operations (TBO). These different lead times determine the main forecasting system, e.g. the flight between SNG and HKG takes around 4 hours, for which nowcasts and near-real-time observations are appropriate and useful, whereas the flight between LHR and JNB is around 11 hours, requiring nowcasts and short-range mesoscale NWP guidance. As a result, it can be expected that the TBO forecasts for the shorter flights have a higher overall skill than for the long-haul flights. Due to this irregularity, developing a consistent methodology for calculating scores and using observations (traditional or novel) between airport pairs is required to determine the improvement of convection forecasts and compare performance across different regions meaningfully. To this end, the World Area Forecast System (WAFS) output should be used as the benchmark to indicate the improvement of the forecasts.

Furthermore, the increasing demand from the aviation industry for greater accountability of weather forecasts prioritises the need for comprehensive verification systems of aviation products. A thorough, objective validation of the improved forecasts will demonstrate the value added and benefits to the aviation community. An overarching topic of various research projects is impact-based forecasts, exploring the best methods to quantify the impacts and benefits of forecasts. New observations can offer the opportunity to evaluate forecast impacts, and their usefulness and applicability should be investigated. However, traditional aviation data and observations, such as PIREP, airport capacity data, air traffic data, aircraft data, etc., are also appropriate for evaluating impacts. The development of measuring benefits may further assist in translating convection hazards to usable TBO impact forecasts, including determining the most fitting parameters to be included. Representatives from the aviation, meteorological and social sciences communities should be involved to provide expert and comprehensive advice on appropriate methods to assess the added value and benefits of the forecasts for aviation. An added benefit of quantifying the benefit of the forecasts can, in some cases, defend expenditures on observing and forecasting system improvements beyond the project.

The verification component of the project should endeavour to make the best use of new observations and apply better and more intuitive verification techniques for aviation products. An ideal outcome will be a proposed standardised suite of verification methodologies to ensure consistency in calculating scores and using observations between airport pairs. In addition, easy availability and effective communication of verification results to the users would ensure maximum uptake and increase confidence in the hazard forecasts.

6. Deliverables and Timelines

6.1. Deliverables

The project will consist of the following 6 deliverables.

- **D1:** Interim Report (by end of 2023). Summary of work so far. Choice of foci for the demonstration phase. Appendix – how we are going to demonstrate and verify these foci
- **D2:** Prototype products ready May 2024
- **D3:** Presentation / Forum (or similar) at ET-MHS Meteorological Hazards Conference (Q3/Q4 2024)
- **D4:** Prototype products demonstrated March 2025
- **D5:** Prototype products evaluated (Covered by final report)
- **D6:** Final Report (by December 2025). Recommendations of relevant product(s) / data.

6.2. Implementation Timeline

	Task / Deliverable (D and then number)	20	21				22				23				24				25			
		Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
No.	**Phase 0 (Initial Phase)**																					
0A	WWRP forming cross-cutting Task Team																					
0B	RB/WWRP endorses the Task Team																					
0C	SC-AVI/ET-MHS representative to join the Task Team																					
0D	Task Team telecon on the scientific plan																					
0E	RB and SERCOM endorse the scientific plan			MS #1																		
0F	Invite project players																					
	Phase 1 (Delivery Phase)																					
1A	Kick off meeting (subject to Pandemic)				MS #2																	
D1	Interim report																					
D2	Prototype products																					
D3	Presentation / Forum (or similar) at ET-MHS Meteorological Hazards Conference																					
D4	Prototype products demonstrated																					
D5	Prototype products evaluated																					
D6	Final Report including recommendations of relevant product(s) / data.																					

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