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AERODYNAMICS LABORATORY

Investigation of Tolerance for Icing of Remotely Piloted Aircraft Systems (RPAS) Rotors / Propellers - Phase 6

Unclassified Unlimited

LTR-AL-2024-0041

29/03/2024

D.M. Orchard

National Research Council Canada
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AERODYNAMICS LABORATORY

Investigation of Tolerance for Icing of Remotely Piloted Aircraft Systems (RPAS) Rotors / Propellers - Phase 6

Volume 1

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ABSTRACT

Over the last five years, the National Research Council (NRC) and Transport Canada (TC) have entered into collaborative research agreements as part of TC's Remotely Piloted Aircraft System (RPAS) Task Force with the objective of creating an evidence-based regulatory framework for safe operation of small RPAS in icing. This work has concentrated on the rotors and propellers of these systems and examined the aerodynamic degradation in terms of reduced thrust and increased power requirements resulting from encounters with icing conditions. This phase of the research program examines the data taken from single rotors exposed to icing, and compares them to the operation of full RPAS systems within similar hazardous environments and, in doing so, enables the development of methods that could be employed to demonstrate the means of compliance of the safe flight in icing.

Using a combination of established icing envelopes related to general and transport category aircraft and employing data obtained from the European Centre for Medium-range Weather Forecast (ECMWF) Reanalysis v5 (ERA5), a range of potentially hazardous icing conditions specific to the operations of small RPAS is presented. These data, along with the aerodynamic degradation observed for small RPAS rotors and propellers, are used to present a framework for the assessment of safe RPAS flight in icing.

NOMENCLATURE

AIWT	Altitude Icing Wind Tunnel
App C	Appendix C
ARP	Aerospace Recommended Practice
C3S	Copernicus Climate Change Service
CAR	Canadian Aviation Regulations
D_{max}	Maximum droplet diameter, μm
ECMWF	European Centre for Medium-range Weather Forecast
ERA5	European Centre for Medium-range Weather Forecast Reanalysis Version 5
ESC	Electronic Speed Controller
FY	Financial Year
FZDZ	Freezing drizzle
FRDA	Freezing rain
H	Horizontal extent in nautical miles
IFS	Integrated Forecasting System
LWC	Liquid Water Content, g/m^3
$\dot{m}$	Mass flow rate of water spray, kg/s
MTOW	Maximum Takeoff Weight, kg
MVD	Median Volumetric Diameter, μm
NRC	National Research Council
RPAS	Remotely Piloted Aircraft System
RPM	Revolutions Per Minute
S	LWC correction factor
s	Ice thickness, m
SAE	Society of Automotive Engineers
SLD	Supercooled Large Drops
sRPAS	Small Remotely Piloted Aircraft System
T	Time, s
TC	Transport Canada
UAV	Unmanned Air Vehicle
UTC	Coordinated Universal Time
V	Air velocity, m/s
V_t	Terminal velocity, m/s
β	Collection Efficiency
ρ_i	Density of ice, kg/m^3

Table of Contents

1 Introduction

Aircraft encounters with icing conditions during flight are recognized as a major safety hazard, with the accretion of ice on critical surfaces leading to the degradation of aerodynamic performance, such as increasing drag, degrading control authority and decreasing lift, along with stall occurring at much higher speeds and lower angles of attack than in a non-icing environment [1]. The threat posed by in-flight icing encounters is particularly concerning for small Remotely Piloted Aircraft Systems (sRPAS) that operate at lower altitudes and lower speeds, where the frequency of icing events is increased and the resulting ice accretion enhanced compared to larger aircraft operating at higher altitudes and speeds. In addition, sRPAS often lack the ability to detect the occurrence of an icing event from which the risk can be assessed and appropriate corrective action performed.

When an sRPAS encounters icing conditions, a particular concern is the degradation in performance of the rotors and propellers. The blades tend to collect ice rapidly, leading to loss of thrust, abrupt increase of power consumption and, with sufficient exposure to the icing environment, catastrophic failure of the vehicle. Considering the potential risks that icing encounters pose to sRPAS operation, Transport Canada's Canadian Aviation Regulations (CAR) 901.35 [2] stipulates that "No pilot shall operate a remotely piloted aircraft system when icing conditions are observed, are reported to exist or are likely to be encountered along the route of flight unless the aircraft is equipped with de-icing or anti-icing equipment and equipment designed to detect icing" and that "No pilot shall operate a remotely piloted aircraft system with frost, ice or snow adhering to any part of the remotely piloted aircraft." However, with the prevalence of expected icing conditions within Canadian airspace and the restrictions the current Regulations may place on effective year-round operations, over the last five years, the National Research Council (NRC) and Transport Canada (TC) have entered into collaborative research agreements as part of TC's RPAS Task Force with the objective of creating an evidence-based regulatory framework for safe sRPAS operations in icing. Phase 1 of this work [3] (FY 18/19) provided an extensive literature review and the acquisition and development of equipment for the simulation of propeller / icing interaction within a wind tunnel environment. Phase 2 of this work [4] (FY 19/20) continued the study with tests being performed on small rotors, i.e., between 0.254 m to 0.356 m (10" to 14") diameter under a range of icing conditions in the NRC Altitude Icing Wind Tunnel (AIWT). This study demonstrated the influence of various icing parameters, e.g., Median Volumetric Diameter (MVD), temperature and liquid water content (LWC), on reducing thrust and increasing power input requirements of sRPAS propellers. These two initial studies were followed by a third phase that extended the work into testing of larger diameter rotors and placed emphasis on the development of a test cell that can provide a realistic simulation of the type of icing conditions an sRPAS will encounter in the Canadian environment, e.g., freezing drizzle and freezing rain. Details of this test rig are provided in a development and calibration report [5] with data obtained from the subsequent testing of a mid-size (22" diameter) rotor blade given in the NRC Laboratory Technical Report LTR-2021-0051 [6].

The work with the larger rotors was continued during the fourth phase of this effort, where further assessments of sRPAS rotors in icing conditions were performed to concentrate on the development of guidance materials and regulations related to the demonstration of means of compliance for flight in icing [7]. By relating the rotor performance under icing in terms of its ability to maintain a minimum thrust output over a predetermined duration, it was possible to demonstrate how sRPAS of varying take-off weights could maintain flight within a safe operational envelope. With the work conducted under this collaborative research agreement, considerable understanding of sRPAS rotor performance in icing has been gained, however, the impact of how this degradation relates to the operation of a full sRPAS needed to be examined. To do this, an outdoor test stand was built at the Montreal Road campus of the NRC that included a spray system calibrated to provide clouds consistent with Appendix C (small drop), freezing drizzle and freezing rain environments [8]. Operating this rig during the winter months enabled the spray to attain supercooled conditions and, therefore, provide an icing cloud into which various sRPAS could be flown.

In all, six sRPAS were tested and showed that the time in which flight in icing could be maintained was as low as 22 seconds for some of the smaller systems examined. Where sufficient data were available, it was shown that above a certain LWC, the time at which the system could sustain flight in icing plateaued and no further increase in water content would result in a reduction in the operational envelope. It was also found that the operational limits of the RPAS were independent of the MVD. Inspection of the ice formed over the full body of an RPAS compared to the ice accretion over the leading edge of the blades indicated that the limited operation of these systems in icing environments was a result of the performance degradation of the rotors compared to that resulting from the increased mass of ice over the full system.

With the data that have been gathered on the performance degradation of a single rotor in icing, along with those obtained from the flight testing, it is now possible to quantify how adverse weather can impact vehicle operation. With this data a regulatory framework that outlines safe operational envelopes for sRPAS based on vehicle platform size and configuration can be developed. This report details the relationship between single rotor performance in icing and that of the full sRPAS in flight and how this information can be used to develop testing criteria and ways to determine means of compliance for safe flight of an sRPAS in icing conditions. Based on additional calibration work that was performed as part of this study, an update to the calculation of Liquid Water Content (LWC) used in the previous test campaigns is presented that enables data from single rotor tests and full sRPAS flight tests to be compared. In addition, the icing environment specific to sRPAS within the Canadian airspace is discussed with the purpose of defining the required test criterion.

From the outset of NRC's work on RPAS icing, the question of the type of icing environment a small RPAS may encounter has been considered based on the operational envelope with a maximum allowable altitude of 122 m (400 ft). The icing conditions specified in the airworthiness standards for transport category airplanes, code of federal regulations (CFR) Title 14 Part 25 Appendix C [9] and O [10] that cover small and large drop icing encounters, respectively, have been previously used as baseline environments in RPAS icing tests conducted by the NRC. Both of these icing environments are seen to be present down to sea level and therefore relevant to the operating altitude of small RPAS.

When considering the operating altitude of small RPAS, additional weather conditions hazardous to sustained operations may also need to be considered, such as freezing precipitation (drizzle and rain), snow, wet snow, ice pellets and mixed phase, e.g., rain/snow mix. With the range of icing threats that a small RPAS may encounter during the winter months and the limitations this may pose on effective year-round RPAS operations under CAR 901.35, a review of expected weather conditions in Eastern Canada and North East United States has been conducted between the months of October to April. To do this, data provided by the European Centre for Medium-range Weather Forecast (ECMWF) Reanalysis v5 (ERA5) that offer atmospheric reanalysis of the global climate covering the period from January 1940 to present [11] have been used. ERA5 is produced by the Copernicus Climate Change Service (C3S) at ECMWF and provides hourly estimates of a large number of atmospheric, land and oceanic climate variables with consistent, gridded historical analyses of state of the atmosphere across the globe [12]. The use of such data to evaluate the icing environment for RPAS operations has previously been conducted for Norway and the surrounding regions [12] as well as for North Europe and metropolitan areas in the United States [13]. Unlike these previous studies that reported conditions from ground level to 9.1 km (30,000 ft), this report focuses on conditions in the low atmosphere (0 to 122 m) pertaining to the operational envelope of small RPAS.

The data provided by ERA5 combine past observations with models to generate consistent time series of multiple climate variables [11] and, therefore, can be used to evaluate the potential occurrence of certain weather conditions including rain, snow, wet snow, mixed phase and ice pellets as well as the presence of low-level clouds that may contain supercooled water droplets and supercooled large drops (SLD). This analysis highlights the potential level of icing risk that exists in the target cities (and wider geographical area) over the winter months as well as providing information on the intensity and range of conditions, data which may be used to form the basis of a regulatory framework to determine methods and measures to be taken by an applicant wishing to demonstrate an RPAS ability for safe flight in adverse conditions.

2 Objectives

Considering the groundwork that has been laid in the previous five phases of this study, showing how the performance of small- and medium-sized RPAS rotors and propellers are impacted by exposure to icing, combined with examining operational characteristics of full sRPAS in similar adverse environments, there is sufficient information for Transport Canada to develop a draft standard for testing sRPAS in icing conditions. This will be performed by collating available data and determining the relationship between single rotor icing characteristics and full system operations, with the aim that this can be improved / completed by industry standards development organizations which, in turn, can be adopted by regulators in defining means of compliance to sRPAS flight in icing.

As part of this effort, it will be necessary to understand the icing environment in which an sRPAS would be expected to operate within Canadian airspace. Until now, sRPAS icing encounters have been assumed to include inadvertent flight through clouds that contain small supercooled water drops as defined by Appendix C of Title 14 of the Code of Federal Regulations Part 25 [9] and by encounters with freezing drizzle and freezing rain precipitation as defined by Appendix O of Title 14 of the Code of Federal Regulations Part 25 [10]. A review of the weather conditions related to potential icing threats (where the maximum operational altitude is limited to 122 m) will be undertaken in order to define a more definitive test environment to be used as part of future facility development and the approach required for demonstrating means of compliance for flight in icing. With the icing environment defined it will then be possible to examine a safe operational envelope for sRPAS based on vehicle platform size and configuration.

3 Assessment of Atmospheric Icing Conditions for Small Remotely Piloted Aircraft Systems

From the outset of NRC's work on sRPAS icing, the question of the type of icing environment such vehicles may encounter has been considered based on the operational envelope with a maximum allowable altitude of 122 m (400 ft). Firstly, the icing conditions specified in the airworthiness standards for transport category airplanes, i.e., Code of Federal Regulations (CFR) Title 14 Part 25 Appendix C [9] and Appendix O [10], that cover small and large drop icing encounters, respectively, have been used as baseline environments in which sRPAS icing tests have been conducted during previous NRC studies.

3.1 Appendix C Icing

Appendix C icing conditions fall into two categories that describe the relationship between MVD, static air temperature and LWC. These are referred to as Continuous Maximum (CM), which has lower LWC but longer horizontal extent of the cloud and a maximum MVD of 40 μm, and Intermittent Maximum (IM), which generally has higher LWC over shorter distances and a maximum MVD of 50 μm. However, as IM icing does not occur below 400 ft, only CM icing is considered as part of the potential flight envelope of the sRPAS. The relationship between drop size, LWC and temperature for Appendix C CM icing is shown in Figure 1.

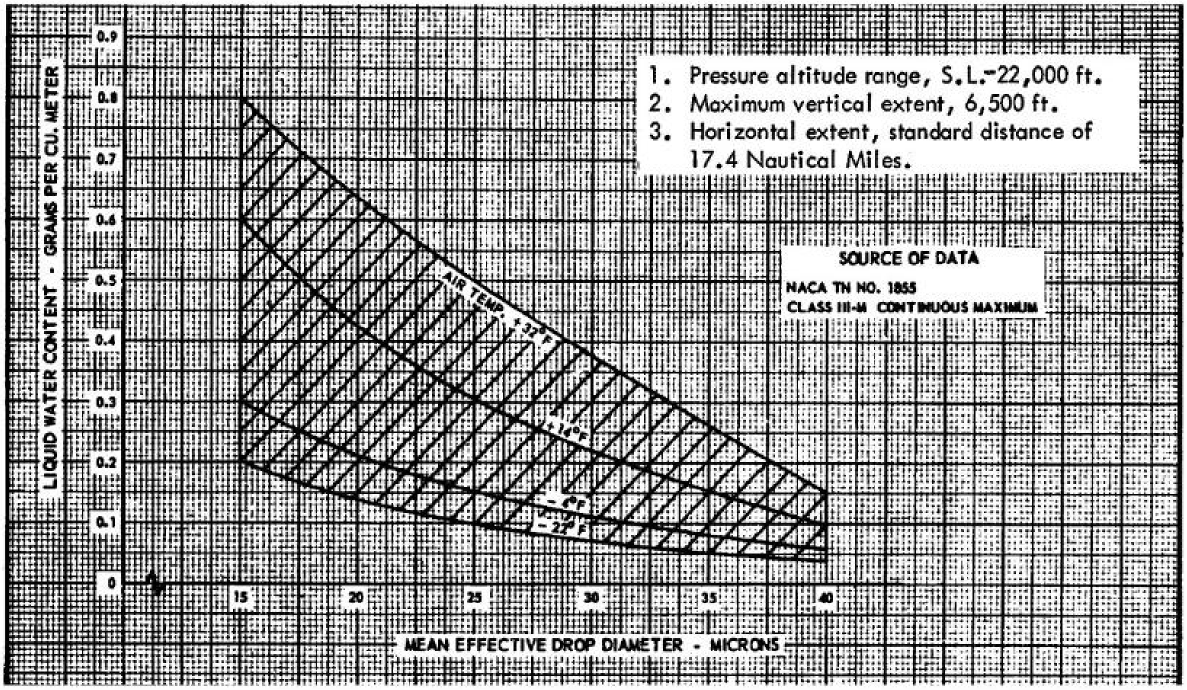


Figure 1: Continuous Maximum Icing Envelope [9]

When considering the Appendix C icing envelope for sRPAS, therefore, the operational limits of the vehicle in terms of minimum temperature should be considered in order to define the range of MVDs and LWCs to which the vehicle would need to demonstrate compliance to safe flight in icing. When defining a test matrix for a particular operational environment, establishing sensitivity of the vehicle to MVD, LWC and temperature should be considered to identify critical points to be included as part of the test plan.

The cloud LWC for CM icing conditions are defined on a fixed distance of 17.4 nautical miles (20 statute miles) and correction for a modified LWC over different horizontal extents should be applied based on the factor given in Figure 2, which can be approximated by,

$$S = 1.83 - 0.31 \log_{10} H \qquad (1)$$

where S is the LWC correction factor and H the horizonal extent of the sRPAS flight in icing in nautical miles. For example, if an sRPAS's expected flight distance in icing was 5 nautical miles, an appropriate LWC under which tests should be performed would be 1.34 times the value obtained from the CM icing envelope given in Figure 1. If, however, the sRPAS was to initiate a landing on detection of an icing encounter and considering (in the worst-case scenario) the icing event occurred throughout the full descent from the maximum operational altitude of an sRPAS, i.e., 122 m (400 ft), a correction factor, calculated using H = 0.066 nmiles (122 m), of 2.7 should be applied to the LWC value obtained from Figure 1.

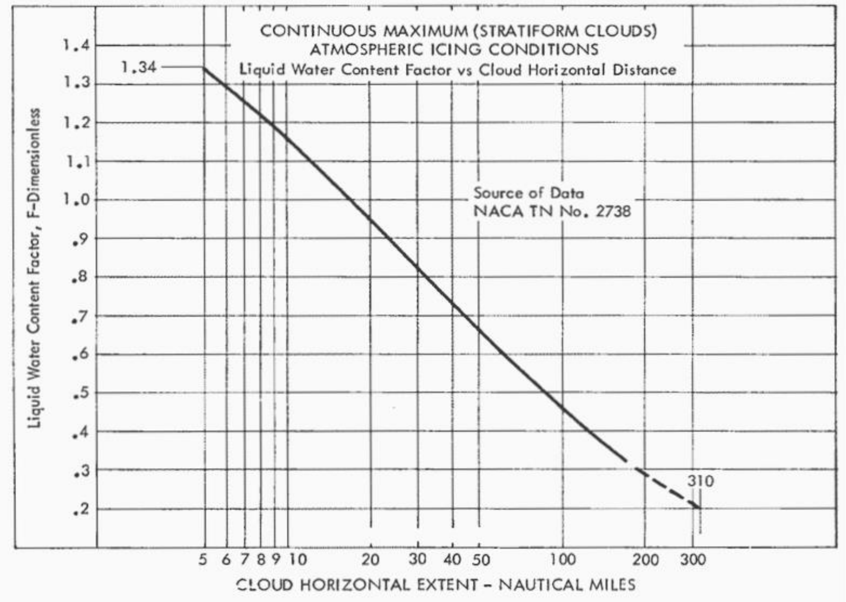


Figure 2: LWC correction factor for horizonal extents other than 17.4 nautical miles [9]

3.2 Appendix O Icing (Freezing Drizzle and Freezing Rain)

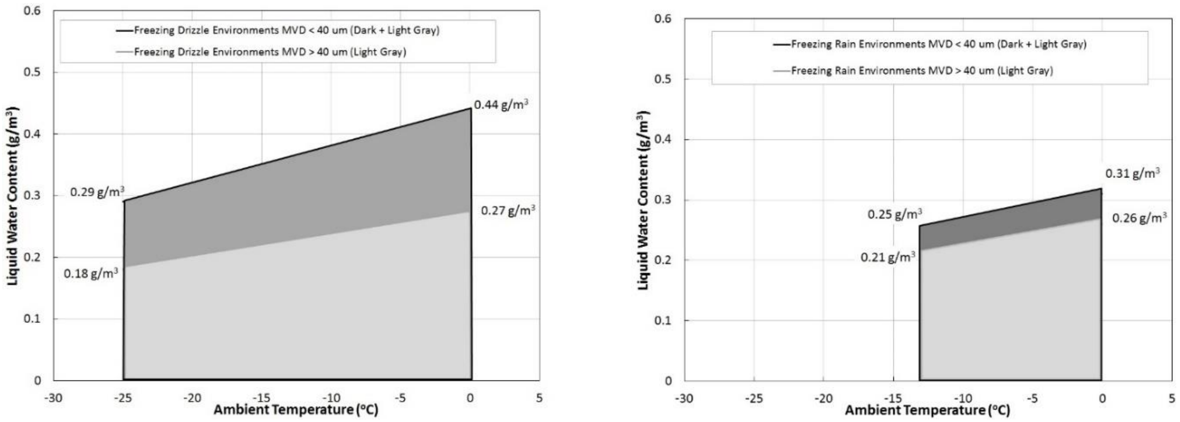
Supercooled Large Drop (SLD) icing can be effectively represented as either freezing drizzle, for which the maximum droplet diameter, D_{max}, is less than 500 µm (denoted by the abbreviation FZDZ), or freezing rain, for which D_{max} is greater than 500 µm (denoted by the abbreviation FZRA). The data are then further segregated into states where the MVD is less or more than 40 µm (Cober et al. [14], Cober and Isaac [15]). These four distinct SLD environments are characterized in terms of MVD and D_{max} as shown in Table 1.

In addition to the larger drop sizes, SLD differs from Appendix C icing by displaying a bi-modal nature across the particle mass distributions. Ideally, during an icing test (or icing simulation) on an sRPAS, the full Appendix O bi-modal spray distribution should be used; however, it is recognised that generating these spray distributions can be challenging and using mono-modal distributions with representative MVDs may be acceptable if these can be demonstrated to provide comparable icing distribution over the sRPAS rotors and propellers.

Table 1: Segregation of SLD conditions

Definition	Abbreviation	MVD (µm)	D_{max} (µm)
Freezing Drizzle	ZLE_in	20	389
	ZLE_out	110	474
Freezing Rain	ZRE_in	19	1553
	ZRE_out	526	2229

Similar to Appendix C icing, as shown in Figure 1, for both freezing drizzle and freezing rain conditions, Appendix O icing envelopes are presented as a variation in LWC over a range of ambient temperatures (see Figure 3), and when choosing the icing envelope for evaluation of the sRPAS, the operational temperature limits of the vehicle would need to be considered during the development of the test matrix. The LWC, ambient temperature and particular icing condition, i.e., freezing drizzle or freezing rain, should be considered when identifying critical operational limits of the vehicle under test.



a) Liquid water content for freezing drizzle **b) Liquid water content for freezing rain**

Figure 3: Liquid water content for Appendix O [10]

As with Appendix C CM icing conditions, the LWC of freezing drizzle and freezing rain has been presented based on a horizontal extent of 17.4 nautical miles, and when considering an alternative distance, correction to the LWC should be made by multiplying by the correction factor given in Figure 4, or by applying the following [10],

$$S = 1.266 - 0.213 \log_{10} H \tag{2}$$

If the sRPAS is to initiate a landing on the detection of an icing encounter and considering (in the worst-case scenario) the icing event occurred throughout the full descent of 122 m (400 ft), a correction factor, calculated using H = 0.066 nmiles (122 m), of 1.8 should be applied to the LWC value obtained from Figure 3.

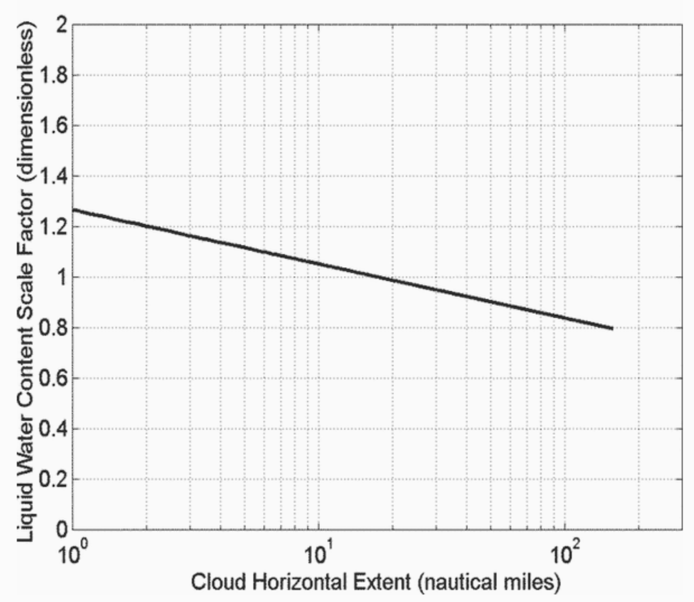


Figure 4: Horizontal extent for freezing drizzle and freezing rain [10]

3.3 Precipitation Icing Threats

In addition to Appendix C and Appendix O (SLD) icing threats that cover encounters with clouds containing supercooled water drops, further consideration should be given to icing conditions in the form of active precipitation. Of these, freezing rain precipitation is considered the most hazardous to the safe flight of sRPAS and, using sample data provided by the European Centre for Medium-range Weather Forecast (ECMWF) Reanalysis v5 (ERA5) [11], an envelope of freezing rain precipitation versus temperature was obtained from data covering Eastern Canada and North Eastern United States between January 2019 and December 2022. As shown in Figure 5, these conditions can occur from just above 0°C down to -19°C at precipitation rates up to 8 L/hr m^2 and, when considering the operational envelope of the sRPAS under test, conditions that represent the potential freezing rain encounters would need to be included as part of the icing test plan. These tests would need to be performed in addition to those developed for the in-flight encounters for Appendix C and Appendix O icing.

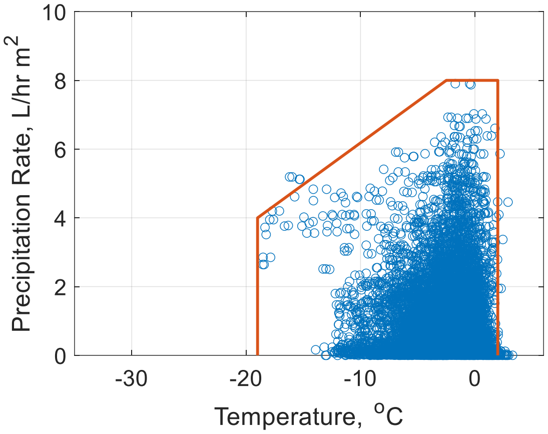


Figure 5: Freezing rain precipitation envelope v temperature

When considering winter precipitation, snow and wet snow play a dominant role in the type of weather conditions that may be encountered by an sRPAS and therefore should be considered as part of the assessment of sustainable year-round operations. As shown in Figure 6, the intensity of snow precipitation can reach 8 L/hr m^2 at ambient temperatures between approximately 2°C and -5°C with a decreased intensity observed at temperatures down to less than -30°C. For such conditions, however, there may not be a particularly negative impact on an sRPAS aerodynamic performance as snow would not tend to accrete to rotors and propellers. When considering wet snow, however, as shown in Figure 7, wet snow occurs in a narrow temperature range of approximately 5°C to -3°C and the possibility of accretion on the lifting surfaces should be considered in terms of degradation of the aerodynamic performance of the vehicle.

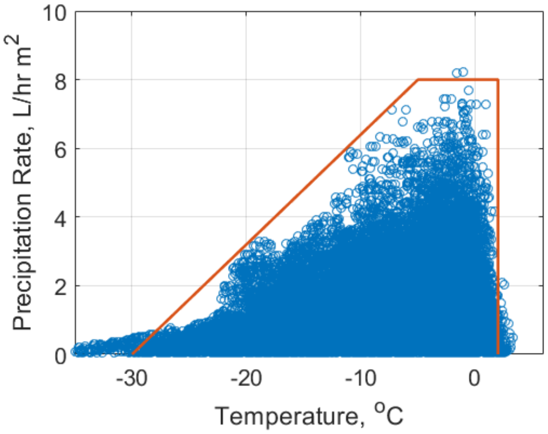


Figure 6: Snow precipitation envelope v temperature

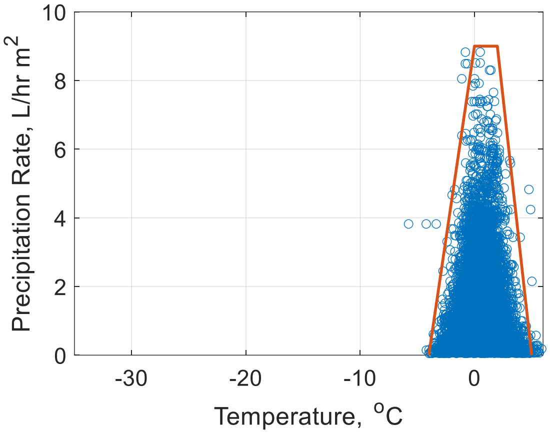


Figure 7: Wet snow precipitation envelope v temperature

Two further precipitation types an sRPAS may experience during winter operations are mixed phase and ice pellets. As shown in Figure 8, however, the majority of the mixed phase occurs above 0°C and only light precipitation is seen down to -2°C. It is considered, therefore, that testing for mixed phase conditions is not required as aerodynamic performance degradation of the rotors would be unlikely and the affect of any accretion that did occur would be demonstrated through tests performed for Appendix C and SLD conditions.

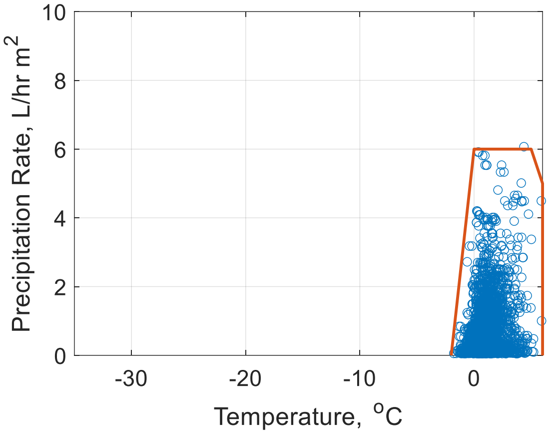


Figure 8: Mixed phased precipitation envelope v temperature

For ice pellets, the range of temperatures and precipitation intensities shown in Figure 9 are similar to that for freezing rain precipitation (see Figure 5). For this condition, however, it is considered that the glaciated particles would bounce off the impacted surfaces with no ice accretion occurring and, as a result, testing in this environment related to performance degradation of the rotors may not be required.

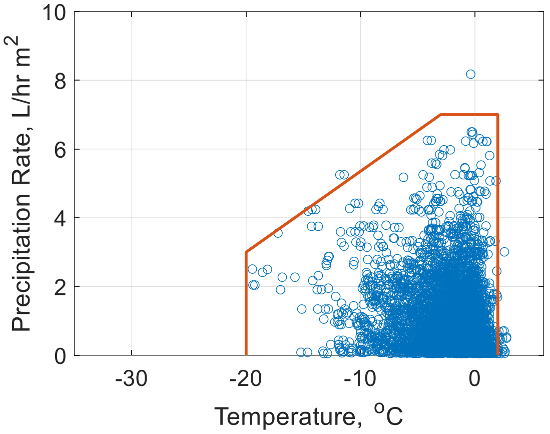


Figure 9: Ice pellet precipitation envelope v temperature

While the data presented above highlight the type of icing threat related to precipitation, it should be noted that these were obtained over a specific geographical region and such information should be analysed on a case-by-case basis considering the expected operational domain of the sRPAS. An example of the type of analysis that can be performed in this regard is given in the following section.

3.4 Icing Conditions Evaluation Criteria

With the range of icing threats that an sRPAS may encounter during the winter months and the limitations this may pose on effective year-round sRPAS operations under CAR 901.35, a review of expected weather conditions in Eastern Canada and North East United States has been conducted between the months of October to April. To do this, data provided by the European Centre for Medium-range Weather Forecast (ECMWF) Reanalysis v5 (ERA5) that offer atmospheric reanalysis of the global climate covering the period from January 1940 to present [11] have been used. ERA5 is produced by the Copernicus Climate Change Service (C3S) at ECMWF and provides hourly estimates of a large number of atmospheric, land

and oceanic climate variables with consistent, gridded historical analyses of state of the atmosphere across the globe [12]. The use of such data to evaluate the icing environment for RPAS operations has previously been conducted for Norway and the surrounding regions [12] as well as for North Europe and metropolitan areas in the United States [13]. Unlike these previous studies that reported conditions from ground level to 30,000 ft, this report focuses on conditions in the low atmosphere (0 to 122m) pertaining to the operational envelope of sRPAS.

The area chosen for the analysis of icing conditions was over a region with latitudes from 42° to 50° North and longitude from 70° to 80° West, as shown in Figure 10, and encompasses population areas as far south as Boston, MA and North to Val-d'Or, QC, and longitudes that include major cities such as Toronto, Ottawa, Montreal and Quebec City.

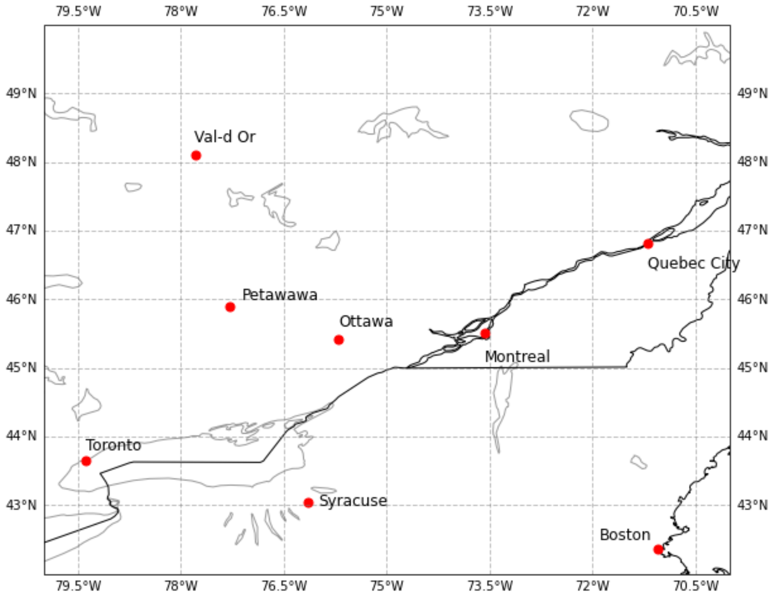


Figure 10: Sample region for ERA5 data gathering

The data downloaded from ERA5 were sampled each day at 6-hour intervals (00:00, 06:00, 12:00, 18:00) over the months in which inclement weather could be expected to occur, i.e., October, November, December, January, February, March and April from January 2019 through to December 2022. The data provided by ERA5 have a horizonal resolution of 0.25°. The analysis of certain weather conditions was performed using the available variables as given in Table 2.

Table 2: ERA5 variables used in weather analysis

ERA5 Name	Unit	ERA5 Description
Latitude	deg	Distance north or south of equator
Longitude	deg	Distance east or west of prime meridian
Time	dd:mm:yy hr:min:sec	
Cloud base height	m	The height above the Earth's surface of the base of the lowest cloud layer, at the specified time
2 metre temperature	K	Temperature of air at 2 m above the surface of land, sea or inland waters.

Total precipitation	m	The accumulated liquid and frozen water, comprising rain and snow, that falls to the Earth's surface. For the re-analysis, the accumulation period is over the 1 hour ending at the validity date and time
Precipitation type	-	The type of precipitation at the surface, at the specified time.
Mean total precipitation rate	kg m^{-2} s^{-1}	The rate of precipitation at the Earth's surface. For the re-analysis, the processing period is over the 1 hour ending at the validity date and time
Maximum total precipitation rate since previous post-processing	kg m^{-2} s^{-1}	The maximum rainfall and snowfall rate at every time since the last postprocessing.

Over the area selected, a three-dimensional array of 33 data points in the latitudinal direction and 41 data points in the longitudinal were provided for each of the variables given in the above table at six hourly intervals throughout the specified dates. A Matlab routine was then used to examine these data to determine the potential weather conditions at each point and whether icing conditions may or may not be present. The follow criteria were used during this analysis.

3.5 Identifying icing conditions

The precipitation parameter describes the type of precipitation at the surface, at the specified time. A precipitation type is assigned wherever there is a non-zero value of precipitation. In the ECMWF Integrated Forecasting System (IFS) [11] there are only two predicted precipitation variables: rain and snow. Precipitation type is derived from these two predicted variables in combination with atmospheric conditions, such as temperature [11]. There are seven possible values that can be assigned to the precipitation type variable as follows,

0: No precipitation
1: Rain
3: Freezing rain
5: Snow
6: Wet snow (i.e., snow particles which are starting to melt)
7: Mixture of rain and snow
8: Ice pellets

Within the Matlab routine, each precipitation type was assigned to a 3D array comprising a 2D grid related to the longitude and latitude locations of the sample area, with the third dimension representing time. For each of these, the main precipitation type provided by ERA5, was interrogated and if a particular precipitation type was seen to be present, then the corresponding location in the 3D array was given a value of one, if the precipitation type was not observed then the corresponding location in the relevant 3D array was given a value of zero.

An example of this approach for snow occurrence across the sample area at 6 pm UTC on 31st January 2022 is shown in Figure 11, where light areas represent locations where the ERA5 analysis indicated snow precipitation and dark areas indicate a non-snow type or clear weather condition.

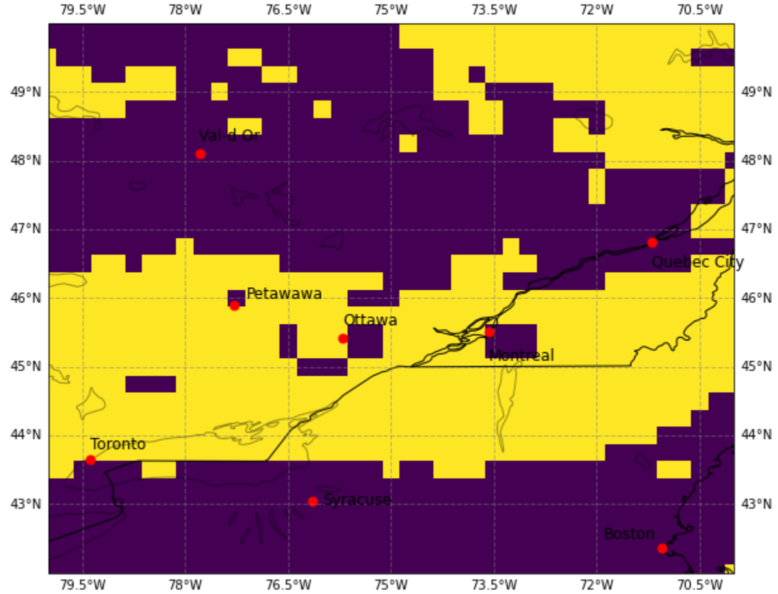


Figure 11: Example of snow precipitation type analysis at 6pm on 31st January 2022. Light areas (yellow) represent areas where ERA5 indicated a snow event at this time with dark (purple) areas indicating a non-snow event

To determine the likelihood of a particular precipitation type occurring at a particular geographical location, the individual precipitation type arrays were then averaged along the time axis.

For each precipitation type, the indicated occurrence (defined as either 1 or 0 in the individual variables) across the sample area was separated into calendar months in order to identify how the potential for icing encounters varied over the winter period considered in this analysis, i.e., October to April.

To determine whether an Appendix C or O (SLD) condition could occur due to an encounter with a cloud containing supercooled water droplets, several steps were required. As most small RPAS operate below 122 m (400 ft), for any condition that indicated a cloud height (or clear conditions) above this altitude, the occurrence of Appendix C or O icing would not be expected. Also, if the temperature at 2 m above ground level was greater than 0ºC, it would be considered that ice accretion would not be likely and the Appendix C occurrence variable was set to 0. Therefore, Appendix C or O conditions were identified for each location and time where the cloud base was below 122 m and ground temperatures were 0ºC or below. In addition, for any location or time where other precipitation, e.g., snow, ice pellets, etc., was already present, then Appendix C or O conditions were not considered. For the remainder of this report, potential encounters with clouds containing supercooled water drops are referred to as Appendix C conditions, although these may also encompass conditions related to large drop icing as defined by Appendix O.

4 Regional weather data

Following the approach previously described, it was possible to examine the potential icing conditions across the sample location for the individual months selected as part of this analysis.

4.1 October

Figure 12 shows the percentage likelihood of any icing event, i.e., snow, freezing rain, Appendix C icing, etc., occurring across this geographical location throughout October. In this, and all subsequent figures showing the icing likelihood over the geographical area, data obtained from the ERA5 with a horizontal resolution of 0.25° are displayed as a linear interpolation using Gourand shading. The data obtained from the reanalysis indicates that, apart from more northerly regions, icing conditions were possible less than 10% of the time. It should be noted that rain is not considered an icing event and is excluded from the analysis. The type of weather conditions, this time including clear skies and rain for completeness, obtained from the ERA5 data across this region for October are given in Figure 13 and shows that 95% of weather conditions are likely to be either clear or raining. The remaining 1%, detailed in Figure 14, mostly indicate the possibility of Appendix C icing, i.e., potential for icing encounters in clouds containing supercooled drops, or mixed phase (snow / rain mix) precipitation.

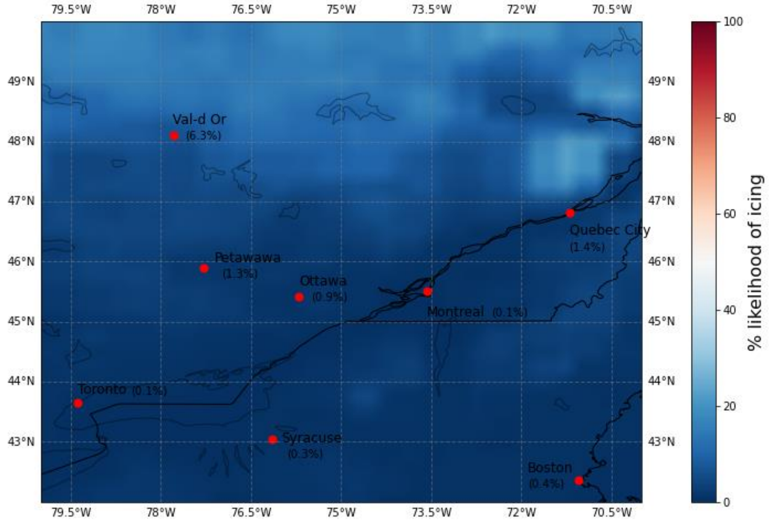


Figure 12: Likelihood of icing events across sample region for October

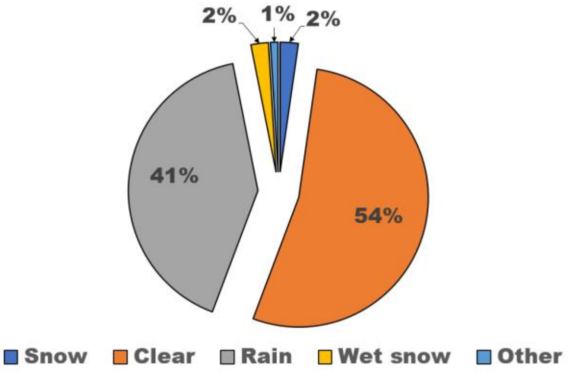


Figure 13: Percentage breakdown of weather conditions for October

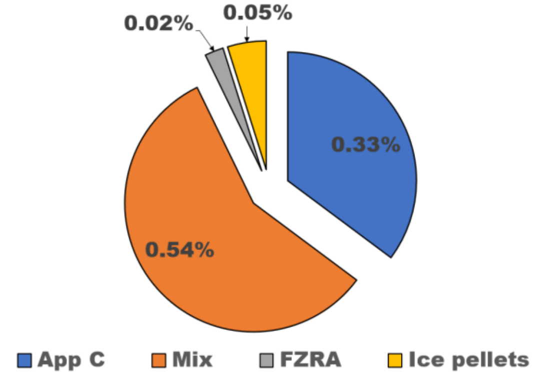


Figure 14: Percentage breakdown of weather conditions for October (other)

4.2 November

Considering the same geographical region for November, Figure 15 shows that the likelihood of an icing event increases at latitudes north of 47ºN to over 60%. Further south, the likelihood of icing has increased to between approximately 10% to 50%. As shown in Figure 16, precipitation in the form of snow and wet snow represents 43% of weather expected for November, compared to 34% for clear conditions and 20% for rain. Of the other 4% of icing condition shown in Figure 17, Appendix C icing and mixed phase conditions show the greatest potential contribution, with the amount of ice pellet and freezing rain precipitation increased from October levels.

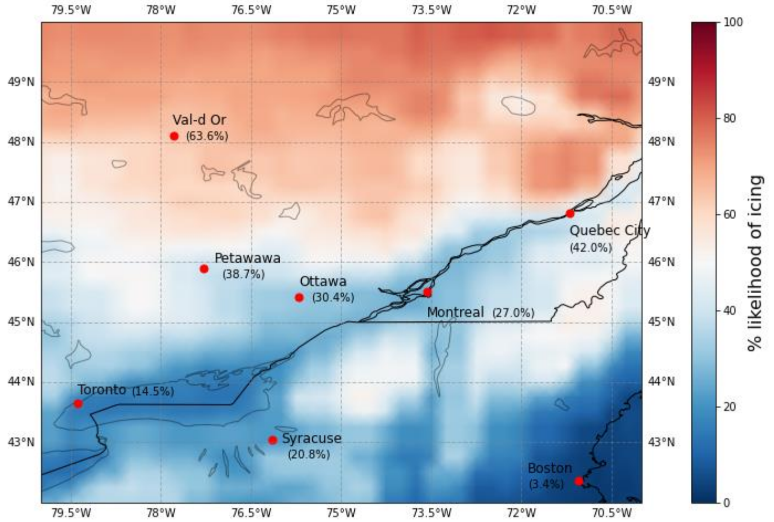


Figure 15: Likelihood of icing events across sample region for November

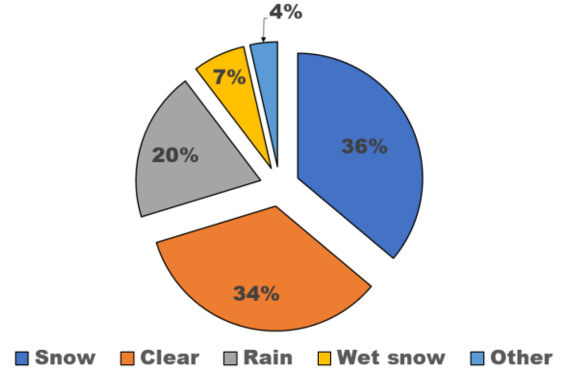


Figure 16: Percentage breakdown of weather conditions for November

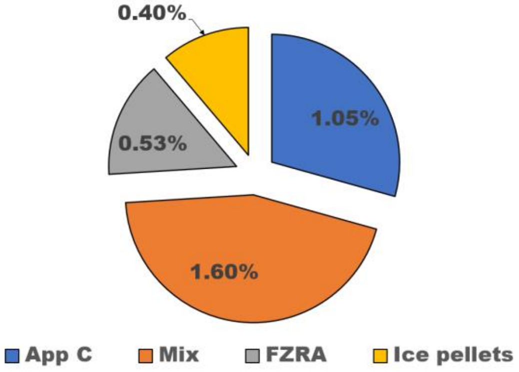


Figure 17: Percentage breakdown of weather conditions for November (other)

4.3 December

For December, Figure 18 shows that the likelihood of an icing event has increased above 50% for most of the sample region. For this time period, Figure 19 shows that the majority of icing events are related to snow and wet snow precipitation with a reduction in the occurrence of rain and clear conditions. For the remaining 3% of icing conditions, detailed in Figure 20, the majority of icing events are comprised of Appendix C icing and mixed phase precipitation. The data also show that the likelihood of freezing rain is increased throughout December.

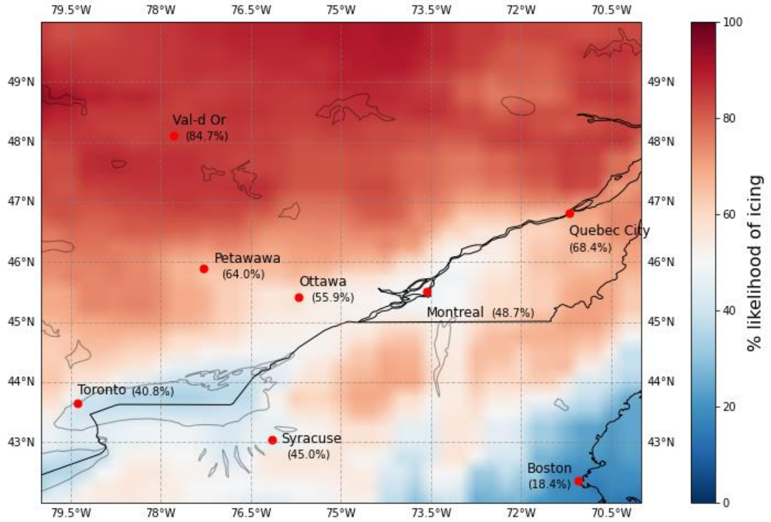


Figure 18: Likelihood of icing events across sample region for December

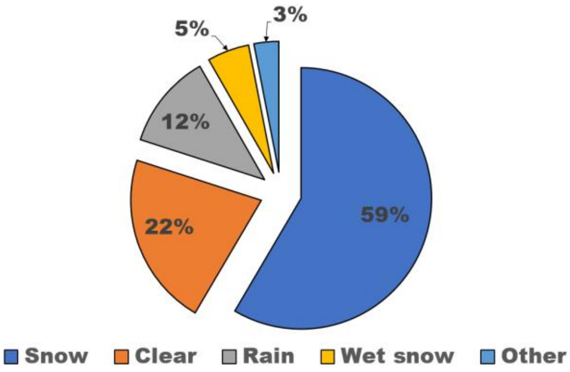


Figure 19: Percentage breakdown of weather conditions for December

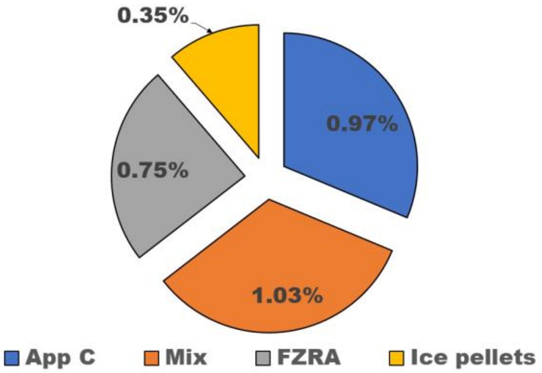


Figure 20: Percentage breakdown of weather conditions for December (other)

4.4 January

For January, Figure 21 shows a similar pattern to December in terms of icing likelihood across the northern regions of the geographical area, with a high potential for icing conditions now extending further south across the St. Lawrence seaway and the upper parts of North Eastern United States. When examining the type of icing conditions that may be present throughout January, Figure 22 shows that snow combined with wet snow (73%) dominates the expected weather events, with a significant reduction in the probability of clear (21%) and rain precipitation (12%) compared to the previous months examined in this study. Considering the remaining icing conditions, shown in Figure 23, Appendix C icing (0.87%) is shown to provide the greatest contribution.

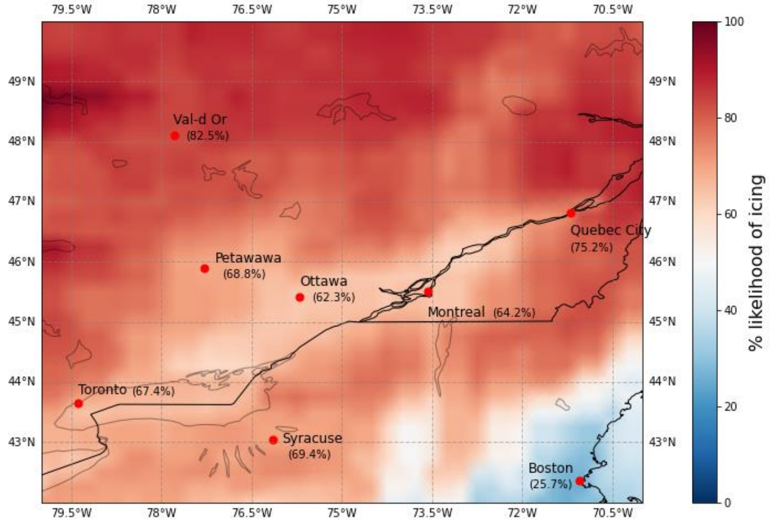


Figure 21: Likelihood of icing events across sample region for January

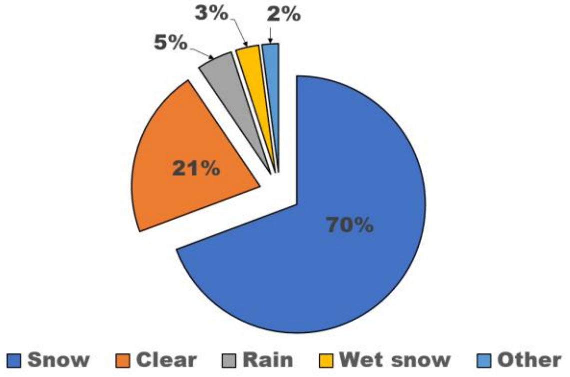


Figure 22: Percentage breakdown of weather conditions for January

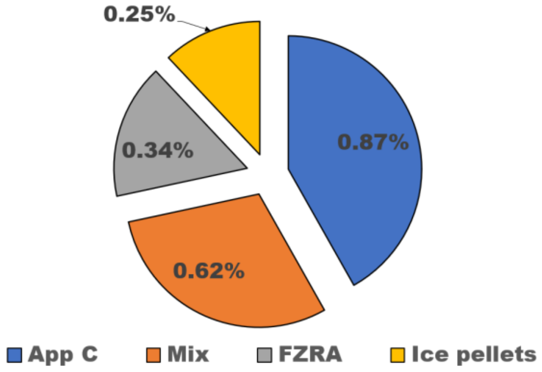


Figure 23: Percentage breakdown of weather conditions for January (other)

4.5 February

The likelihood of icing in February, shown in Figure 24, indicates a similar pattern to that of January with a slight reduction in icing occurrence in the northern parts of this region. Snow and wet snow (67%) still dominate the weather conditions, as shown in Figure 25, with likelihood of clear conditions (27%) increasing slightly whereas the likelihood of rain (5%) remains similar to that seen in January. Of the 3% that makes up the remaining icing conditions, shown in Figure 26, freezing drizzle precipitation (0.89%) has increased compared to the previous months examined and makes up the majority of the weather events for this part of the overall weather analysis. Appendix C (0.81%) remains consistent with values seen for November, December and January.

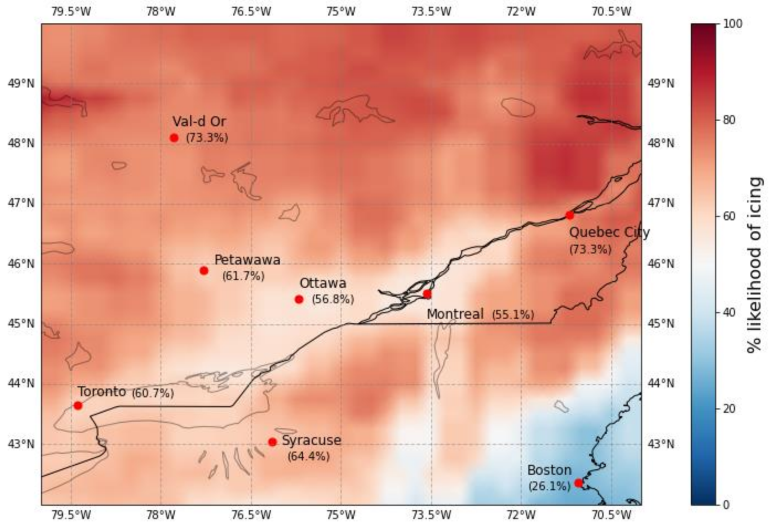


Figure 24: Likelihood of icing events across sample region for February

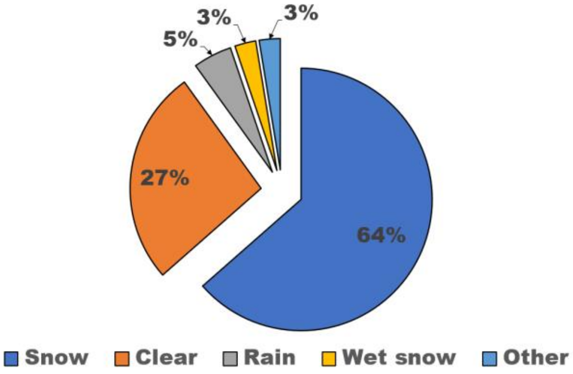


Figure 25: Percentage breakdown of weather conditions for February

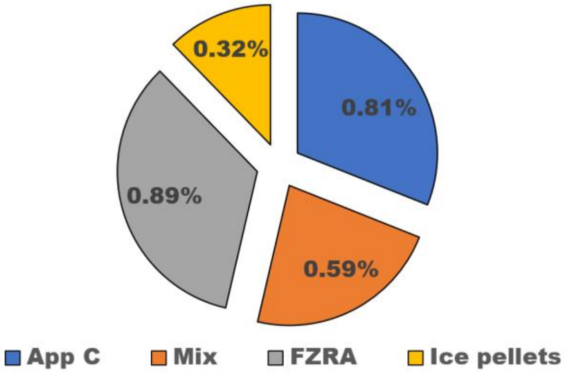


Figure 26: Percentage breakdown of weather conditions for February (other)

4.6 March

For March, the likelihood of icing shown in Figure 27, gives a similar pattern to that for November with higher possibility of icing events occurring north of 47ºN. Icing events around Lake Ontario and along the St. Lawrence seaway, a region encompassing Toronto, Ottawa and Montreal, are indicated to have reduced during March between approximately 20% to 30%. For this month, clear (40%) combined with rain (13%) conditions are seen to dominate the overall weather conditions with snow combined with wet snow making up 44% of the overall icing likelihood. Of the other icing conditions, e.g., freezing rain, Appendix C, etc. mixed phase conditions are seen to provide over 1% to the overall contribution to icing events with Appendix C (0.51%), freezing rain (0.43%) and ice pellets (0.29%) providing the remainder.

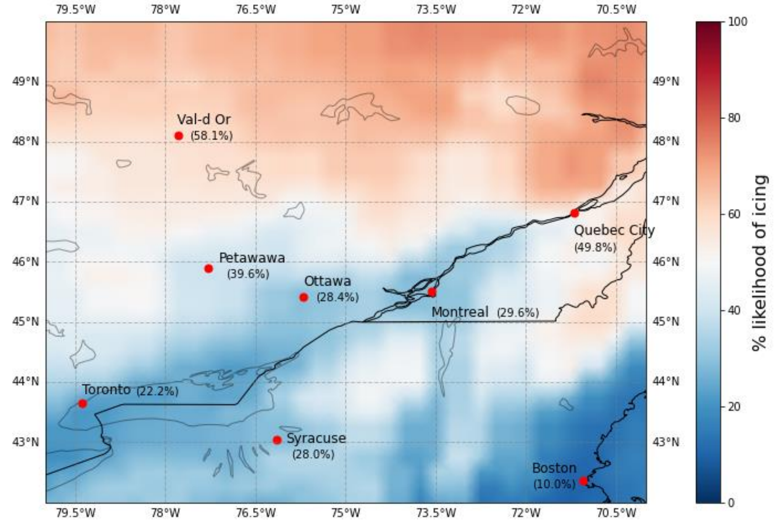


Figure 27: Likelihood of icing events across sample region for March

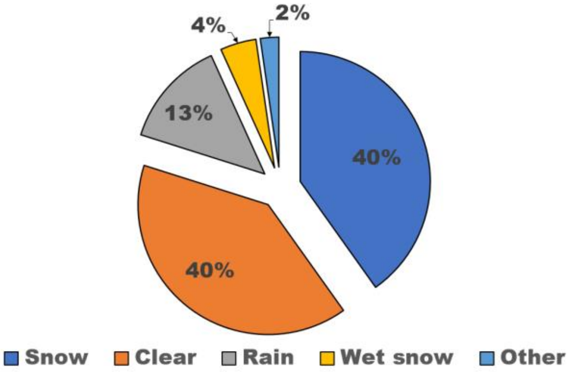


Figure 28: Percentage breakdown of weather conditions for March

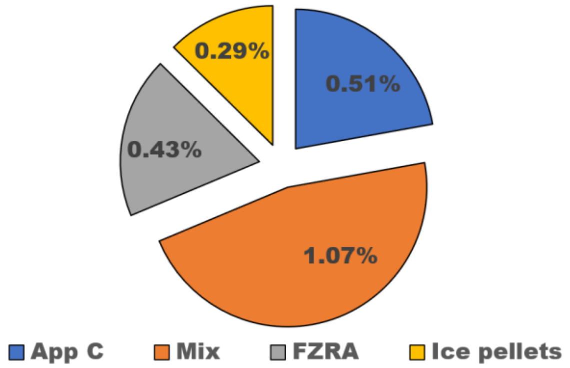


Figure 29: Percentage breakdown of weather conditions for March (other)

4.7 April

While considered to be early spring in the sample location, Figure 30 shows that the likelihood of an icing event in April is still elevated, particularly in the northeastern part of the sample area, i.e., north of Quebec City, with the possibility of an icing event shown to be 50% to 60%. Further south, the likelihood of an occurrence of adverse weather has reduced to 20% and below. The breakdown of the weather conditions for the entire region, shown in Figure 31, shows that non-icing events, i.e., clear (51%) and rain (24%) dominate the weather conditions for April with the combination of snow and wet snow reduced to 23% of the overall conditions. As with March, for the other icing events contributing to the overall weather conditions throughout April, mixed phase icing (1.57%) is seen to be dominant when compared to Appendix C, freezing rain and ice pellets.

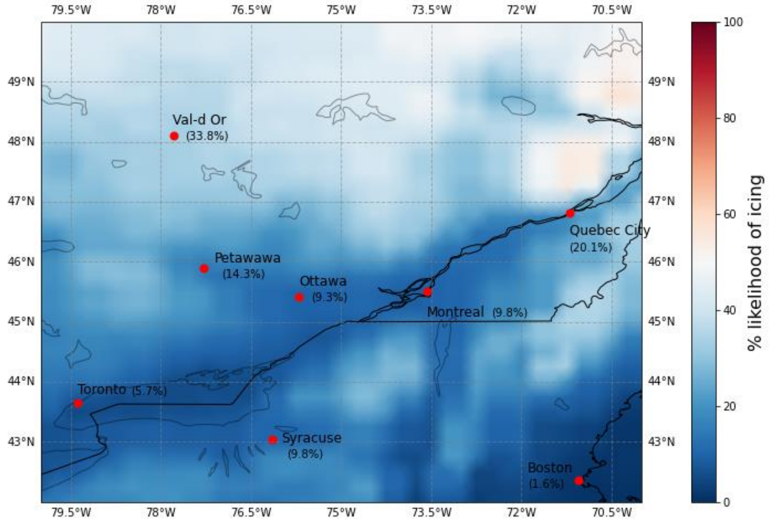


Figure 30: Likelihood of icing events across sample region for April

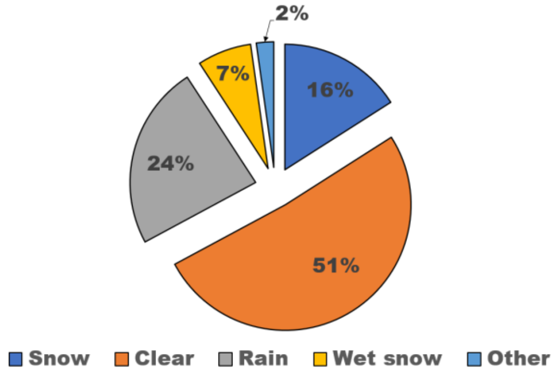


Figure 31: Percentage breakdown of weather conditions for April

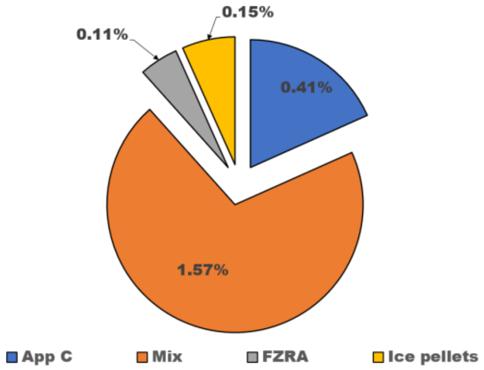


Figure 32: Percentage breakdown of weather conditions for April (other)

4.8 City-specific weather data

In the previous section, the ERA5 data were used to demonstrate the likelihood of icing over the sample geographical region and specify the particular weather conditions and their likelihood of occurrence over the winter months. While providing useful information regarding the icing threat to sRPAS, the area chosen covered a large region in which extremes of weather may vary over the 8° of latitude (42ºN to 50ºN) and be affected locally by geographical features such as lakes and regions of high elevation. When it comes to assessing the likelihood of icing related to proposed RPAS operation, it may be necessary to review these data over smaller areas as they pertain to specific regions and flight paths.

The data provided so far have, therefore, been further analysed over smaller regions that cover four major cities, i.e., Toronto, Ottawa, Montreal and Quebec City, to assess the icing threat for winter RPAS operations in urban environments.

A breakdown of the weather conditions in Toronto between October and April is given in Figure 33. Figure 34 and shows that there is an almost zero likelihood of icing conditions in October, with snow, wet snow and other icing conditions representing less than 0.15% of the overall weather conditions present throughout this month. This is similar to the conditions in April, although here there is an increased likelihood of snow and wet snow (3.9%) and a slightly higher possibility (0.8%) of other icing events, Appendix C, freezing rain, etc.

Snow and wet snow are shown to dominate the weather conditions throughout December, January and February and, when considering the contribution from the other icing events, the highest likelihood of Appendix C (0.6%) and freezing rain (1%) occurs throughout February.

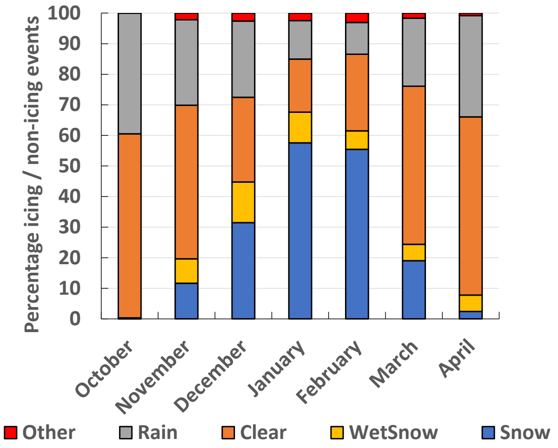


Figure 33: Percentage breakdown of weather conditions in Toronto from October to April

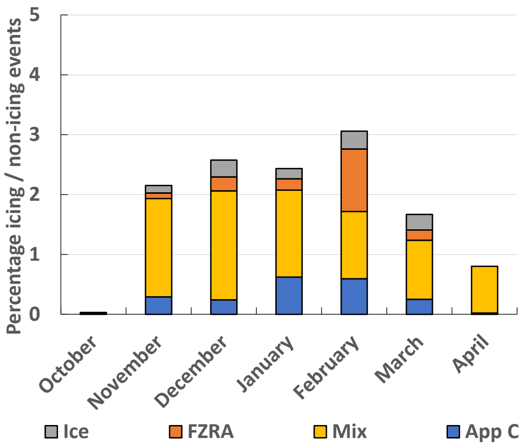


Figure 34: Percentage breakdown of other weather conditions in Toronto from October to April

When reviewing the winter icing conditions for Ottawa, shown in Figure 35 and Figure 36, the overall breakdown of weather conditions is similar to that for Toronto, although here there is a greater contribution from other icing events that include Appendix C and freezing rain. As shown in Figure 36, there are higher components of freezing rain events across the months from November to March and considerably more occurrence of Appendix C icing, particularly in October and November.

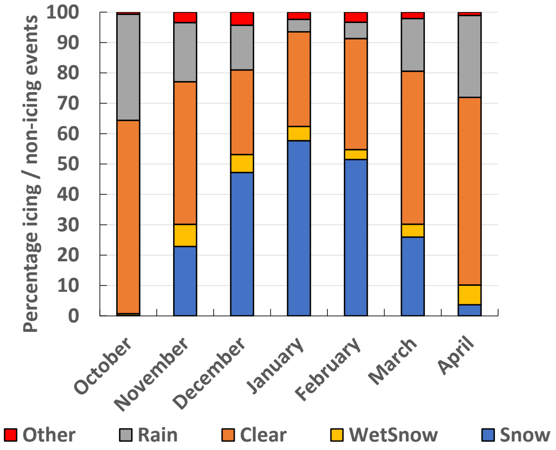


Figure 35: Percentage breakdown of weather conditions in Ottawa from October to April

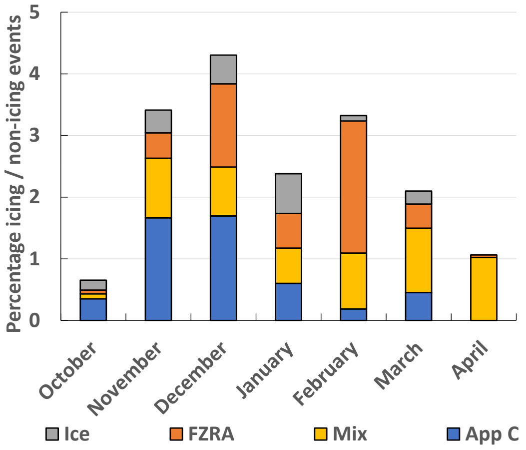


Figure 36: Percentage breakdown of other weather conditions in Ottawa from October to April

For the assessment that focuses on Montreal, as shown in Figure 37 and Figure 38, the weather conditions are very similar to those of Toronto. For the other weather conditions shown in Figure 38, mixed phase conditions appear to dominate from November through to April, with the exception of February that shows a slightly greater contribution from freezing rain (1.4%).

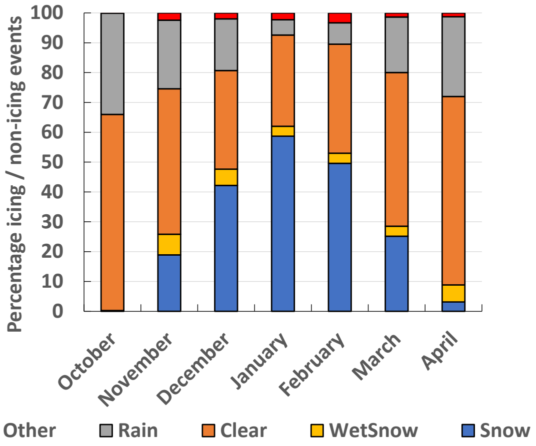


Figure 37: Percentage breakdown of weather conditions in Montreal from October to April

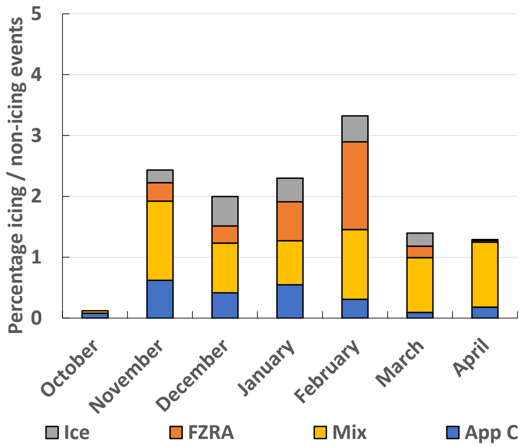


Figure 38: Percentage breakdown of other weather conditions in Montreal from October to April

For Quebec City, shown in Figure 39 and Figure 40, there is more likelihood of snow events across all months compared to the other cities examined, peaking to 77% in January. Contributions from other icing conditions, such as Appendix C and freezing rain, are reduced during the months of December, January and February, but have higher contributions throughout November, March and April.

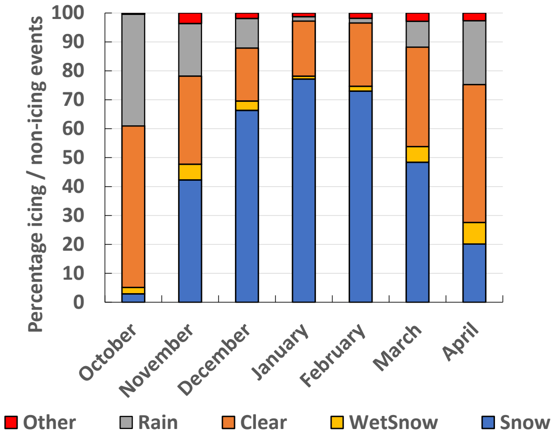


Figure 39: Percentage breakdown of weather conditions in Quebec City from October to April

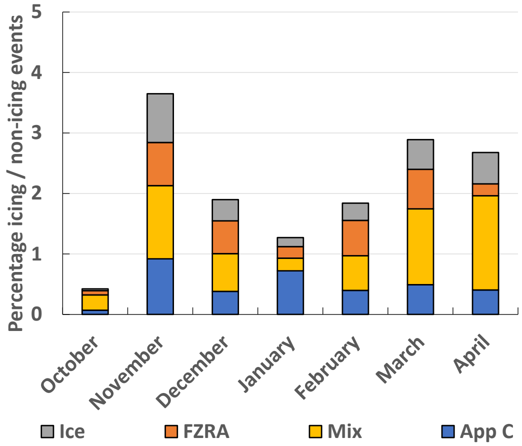


Figure 40: Percentage breakdown of other weather conditions in Quebec City from October to April

5 Single Rotor Icing Assessment

The assessment of aerodynamic performance of single rotors in icing has been conducted as phases 3 and 4 [6] [7] of the work performed to date related to sRPAS flight in adverse weather conditions. This has been performed within a climate-controlled room [5] with the rotor operated in the horizontal plane underneath an array of spray bars that provide a calibrated icing cloud. An example of an sRPAS rotor installed on the test stand beneath the spray nozzle array is shown in Figure 41.

The test stand consists of an RC Benchmark (Tyto Robotics Inc.) Series1780 Dynamometer 25kgf-100A: Single-motor, a XOAR Titan T8110 140KV brushless electric motor and a Xoar Pulse P80 electronic speed controller (ESC). The dynamometer is equipped with load cells and accelerometers to directly measure torque, thrust and accelerations due to vibrations, respectively. It also provides direct measurements of voltage, current, RPM, and motor winding resistance.

Figure 41: Spray system and rotor thrust stand installed in cold room

5.1 Calibrating the Spray Cloud

As part of the original calibration of the spray cloud in the cold room [5], the LWC was calculated based on a prediction of the drop terminal velocity, V_t, from which the LWC could be calculated by,

$$LWC = \frac{\dot{m}}{Area\,.V_t} \tag{3}$$

where $\dot{m}$ is the mass flux of the spray measured over predetermined *Area* using an array of capture tubes. When calculating V_t, an assumption has to be made regarding the drag coefficient of the water drops, which, at the low Reynolds numbers associated with the small drop sizes and velocities, may result in uncertainty in the calculation.

It was, therefore, decided as part of this phase of the work on sRPAS icing to perform a direct measurement of LWC using the icing blade measurement described by Stallabrass [16] using flat plates attached to a rotating arm assembly installed on the test stand motor. The rotating arm assembly is shown in Figure 42 and includes two 3.19 mm thick x 40 mm long aluminum plates attached to the end of arms supported to the motor drive by a central hub.

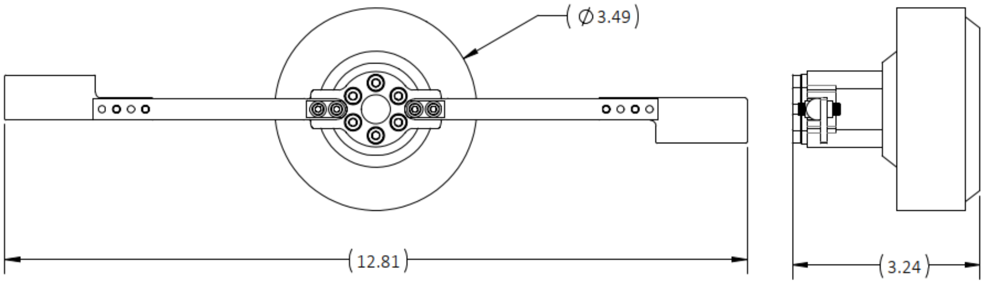


Figure 42: Rotating arm with icing blades

The arm was rotated at a fixed speed in the clockwise direction (with the icing cloud activated) for a pre-set time and the resulting thickness of ice accreted to the 3.19 mm edge of the flat plates measured. From this the LWC could be calculated using,

$$LWC = \frac{\rho_i s}{\beta\, V\, T}$$

where, ρ_i is the density of ice, s is the ice thickness, β the collection efficiency of the icing blade, V the radial velocity at the centre of the flat plate (at a radius of 122.7 mm) and T the exposure time in the icing cloud. All rotating blade measurements were conducted at a rotational speed of 500 RPM and a cold room temperature of -18ºC to ensure all water froze on impact. An example of the icing blade assembly and close up of ice accreted on the blade leading edge is shown in Figure 43 and Figure 44, respectively.

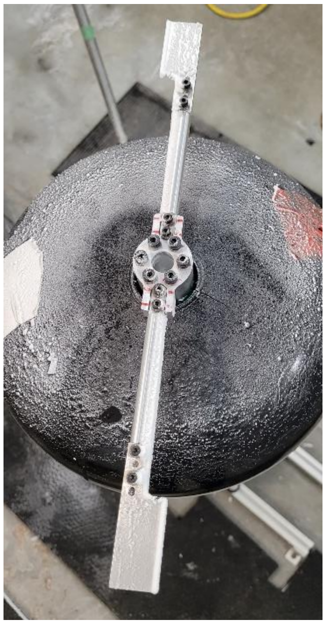


Figure 43: Icing blade assembly installed on RPAS rotor test rig

Figure 44: Ice accreted to the leading edge of icing blade

An example of the LWC measurements taken with the icing blade over a range of water flow rates and MVDs is given in Figure 45.

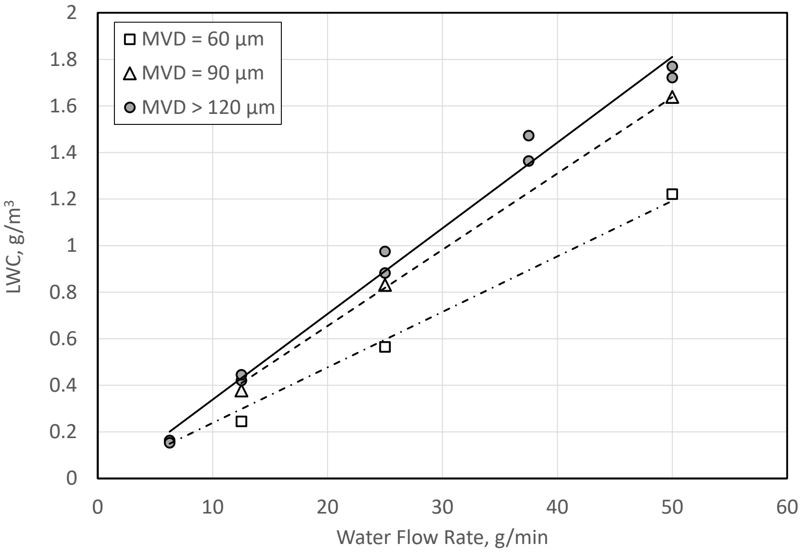


Figure 45: LWC measurements using rotating icing blade

6 Comparing Single Blade and RPAS Performance in Icing

As part of phase 5 of the NRC work in the investigation of tolerance for icing of sRPAS [8], a series of different sRPAS were flown (in hover mode) in a calibrated icing cloud. This was performed in a dedicated icing rig assembled outside during winter 2022-23 with the objective to assess the time each sRPAS could maintain flight when exposed to a range of icing conditions, thereby extending the work on the single rotor performance to the operation and control of full systems.

For one particular sRPAS, it was possible to download system performance data, from which the power requirements of the rotor drive motors could be calculated. An example of this analysis is shown in Figure 46 for icing conditions at a static temperature of -7 ºC, an MVD of 120 µm and a nozzle water flow rate of 100 g/min, that, considering the modified LWC calibration discussed in section 5.1, relates to a LWC of 3.7 g/m^3. The data show that a maximum power of approximately 230 W is reached on the front right motor shortly before the flight was terminated at 49 seconds. A further example of the motor performance during flight in icing, at a static temperature of -7 ºC, is shown in Figure 47 for conditions where the MVD = 200 µm and the nozzle water flow rate was 25 g/min (LWC = 1.0 g/m^3). Under these conditions, the ability of the system to maintain flight was extended to approximately 136 seconds.

In both examples presented in Figure 46 and Figure 47, and for all tests performed with this particular sRPAS, the ice accretion on the rotor blades resulted in an increase in motor power to provide the required thrust necessary to maintain hover. In all cases, once the motor power reached a maximum of 230 W, the sRPAS was no longer able to maintain the required thrust and the system descended out of the test area towards to ground. At this point, the system was considered to have reached its limit of operational capability in icing.

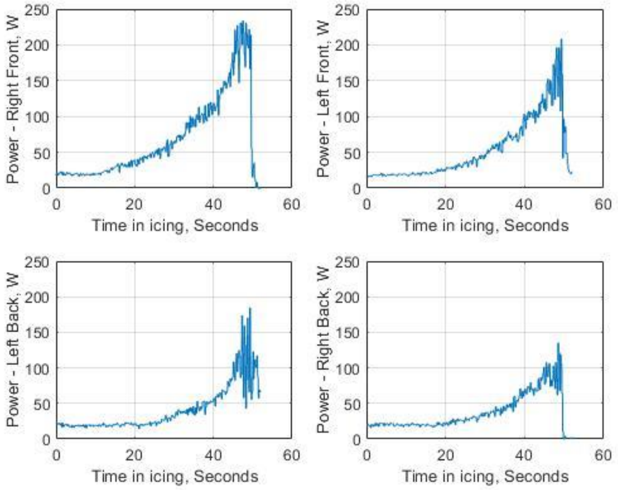


Figure 46: Motor power for sRPAS during flight under icing conditions with static temperature = -7 °C, MVD = 120 µm and nozzle water flow rate = 100 g / min (LWC = 3.7 g/m^3)

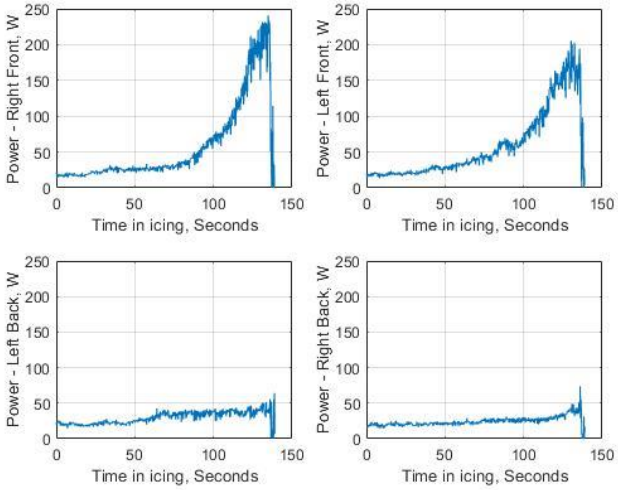


Figure 47: Motor power for sRPAS during flight under icing conditions with static temperature = -7 °C, MVD = 200 µm and nozzle water flow rate = 25 g / min (LWC = 1.0 g/m^3)

Knowing the maximum power available to each of the sRPAS motors, it was possible to simulate the performance of an individual rotor in icing using the test stand in the cold room (see section 5) with the objective of correlating the data obtained from this test set up with those of the full sRPAS. The single rotor of the sRPAS installed on the test stand is shown in Figure 48.

Figure 48: RPAS blade installed on RPAS rotor test rig

To compare a single rotor performance to that of a full sRPAS operated in hover mode, as described above, it was necessary to calculate the thrust required from each rotor using equation 4.

$$\text{Thrust per rotor} = \frac{RPAS\ MTOW\ (kg) \times 9.81 (\frac{m}{s^2})}{number\ of\ rotors} \tag{4}$$

where *RPAS MTOW* is the maximum takeoff weight of the 4 rotor sRPAS, i.e., 1.39 kg, and resulted in a required thrust for a single rotor of 3.41 N. Once the icing spray was started, the motor power was increased to maintain this single rotor thrust requirement. The time taken from the initiation of the icing cloud to the test stand control system indicated a maximum power requirement of 230 W was recorded as the duration a single rotor could maintain flight in the particular icing condition. The test conditions for the single rotor tests were chosen to correspond to the range of test conditions conducted for the outdoor full sRPAS icing tests; these are provided in Table 3. It should be noted that the LWCs shown in the table are higher than those specified for Appendix C and Appendix O conditions as these were chosen for demonstration purposes when comparing performance of the full system to single rotors on the cold room rotor test rig.

Table 3: Test conditions for single RPAS rotor

MVD, µm	Water Flow Rate (WFR), g/min	LWC, g/m^3	Cold room temperature, °C
30	50 - 150	1.72 – 8.31	-10
120	14.1 - 160	0.5 - 6	-10
200	15 - 150	0.51 – 5.36	-10

The time taken for the single rotor motor power to reach 230 W compared to the time in which the sRPAS was able to maintain flight in equivalent icing conditions are shown in Figure 49, Figure 50 and Figure 51 for MVDs of 30 µm, 120 µm and 200µm, respectively.

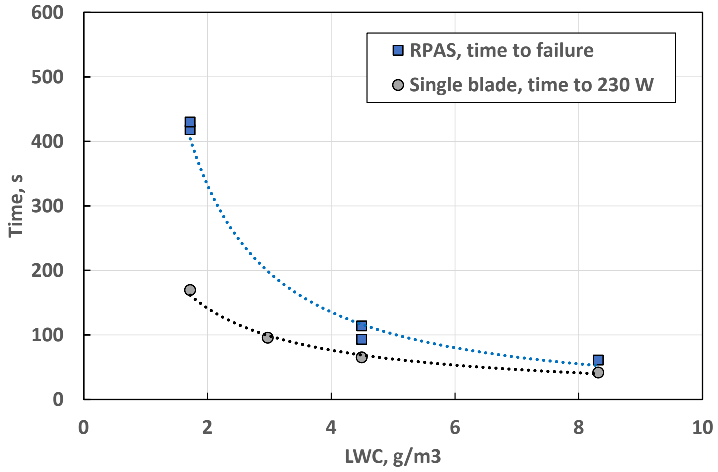


Figure 49: Comparison of single rotor performance and full RPAS in icing at MVD = 30 µm

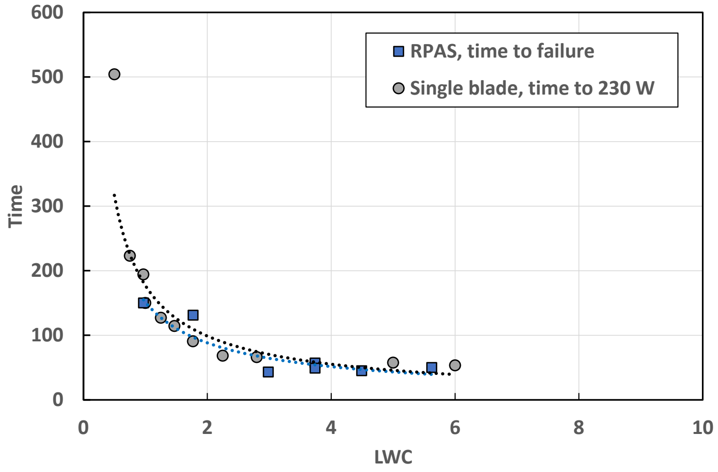


Figure 50: Comparison of single rotor performance and full RPAS in icing at MVD = 120 µm

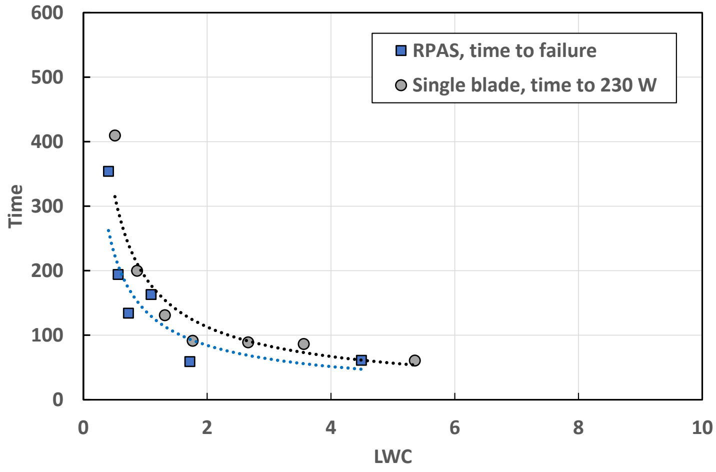


Figure 51: Comparison of single rotor performance and full RPAS in icing at MVD = 200 µm

As shown in Figure 49, over the majority of the LWC values tested, the time for the single rotor to reach the maximum power requirement of 230 W is shorter when compared to the available flight time obtained from the full sRPAS tests. This is considered to be due to recirculation of the spray cloud within the cold room leading to an accumulation of the water content as the test progresses, whereas similar accumulation would not occur in the outdoor test environment. Despite the differences between available time in icing indicated by the single rotor and full sRPAS tests, the single rotor provides a more conversative approach when considering this as means to demonstrate compliance for flight in these particular icing conditions.

For the test cases with larger MVDs, shown in Figure 50 and Figure 51, the comparison between the single rotor and the full sRPAS results shows a close comparison in predicting the available flight time in icing across all conditions tested. For the larger MVDs, less recirculation of the spray cloud is observed in the cold room and therefore there is a closer match in the water concentrations between the cold room and outdoor icing environments.

While the available flight times show close comparison, particularly for the larger drop size icing conditions, the time history of the motor power and RPM during the icing event obtained between the single rotor and full sRPAS, see Figure 52 (a) and (b), show that certain differences in operational characteristics exist. For example, for the test point conducted at -7ºC at an LWC of 3.7 g/m^3 and MVD of 120 µm, the motor power in dry conditions for the single rotor is approximately 75 W compared to 20 W for the full sRPAS whereas the corresponding RPM for the full sRPAS is higher (4750 RPM) than that of the single rotor (4300 RPM).

Following initiation of the icing cloud, the sRPAS motor power increases faster than the single rotor configuration whereas the increase in corresponding RPM stays relatively consistent between the two systems. While the single rotor and full sRPAS motor performance, conducted as part of the current study, has shown how comparing the two can be used to quantify operation in icing, the differences observed in the motor characteristics highlight the importance in matching the motor control systems and flow fields around the rotors between the full and single system tests. In the current test comparisons, the electronic speed controllers (ESC) and motors differed between the full sRPAS and single rotor configurations, and the flow path immediately beneath the single rotor had more obstruction than that of the sRPAS as a result of the shroud installed around the test stand assembly. Both of these differences may have led to the changes observed in the power and RPM characteristics.

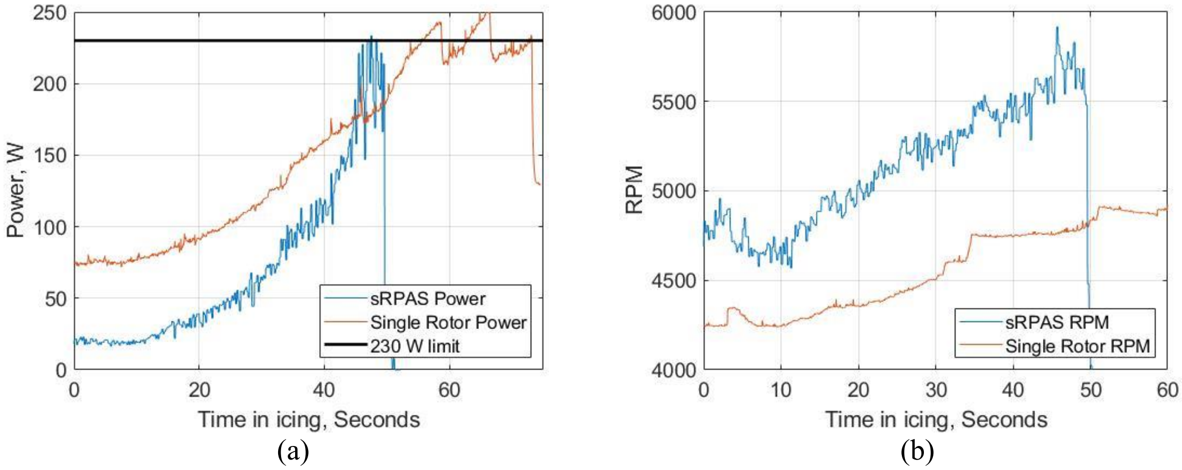


Figure 52: Comparison of power and RPM for sRPAS motor and for single rotor with static temperature = -7 °C, MVD = 120 µm and nozzle water flow rate = 100 g / min (LWC = 3.7 g/m^3)

7 Evaluating Means of Compliance for sRPAS Flight in Icing

With the work that has been performed to date on the assessment of the tolerance for icing of sRPAS, an initial framework can be developed that identifies the steps by which compliance for flight in icing can be demonstrated by a potential applicant.

7.1 Selecting the Icing Environment

When demonstrating safe flight of a RPAS in icing, it is recommended that physical testing is performed on either a single rotor or full RPAS in a calibrated environment that represents the proposed flight envelope using the range of potential weather encounters, as discussed in section 3.

7.2 Testing of Single sRPAS Rotors

When demonstrating safe flight in icing using a single rotor, a number of factors need to be considered to define the required operational characteristics and limits regarding an ability to maintain flight.

- **sRPAS weight and number of rotors**. If an sRPAS is designed to land following the onset of icing, it is considered that, as a minimum, the thrust required from each rotor should be sufficient to maintain the RPAS in hover, as calculated by equation (4) and supplemented by an appropriate factor of safety based on the operational characteristics of the sRPAS. However, if the vehicle is designed to maintain flight in icing, the thrust calculation should be modified to reflect that required to maintain the flight path.
- **Individual motor power**. The maximum power of each sRPAS motor should be identified and this value used to identify the power limits during the single rotor test.
- **Flight duration**. What are the operational requirements of the RPAS following an icing encounter?
  - If a vehicle is required to land following the onset of icing, the rotor should be required to supply sufficient thrust to maintain hover for the time it takes the sRPAS to safely land from its maximum operational altitude.
  - If the vehicle is designed to continue its flight following icing onset, the time to complete

the flight path should be used as the required duration.

The single rotor shall be installed on a thrust stand / motor that can control the rotational speed and monitor and record the thrust, torque and power requirements during operation. Ideally, the ESC and motor assembly as well as the external flow field around the single rotor test stand should represent that of the full sRPAS design. Any de-icing or anti-icing devices associated with the rotor should be included without modification from the design when installed on the sRPAS.

Thrust, torque and power requirements of the rotor should be recorded throughout the icing process and compared to operation in dry air.

7.3 Testing of Full RPAS in Icing

When demonstrating safe flight in icing using a full system, the test facility should be capable of allowing unrestricted flight of the sRPAS while maintaining a consistent icing environment (cloud uniformity) over the area covered by the vehicle. It is recommended that the flight is recorded via video and an indication of icing spray activation be given as part of the data set. It is recommended to perform measurement of the weather conditions in close proximity to the test platform throughout the duration of the sRPAS flights.

When the RPAS is required to land following the onset of icing, safe flight can be demonstrated by maintaining hover for the time it would take for the RPAS to safely land from its maximum operational altitude. If the vehicle is designed to continue along the flight path following icing onset, the time of the entire flight path should be used and correction should be made to account for the higher thrust required for continued forward flight or ascent.

7.4 Facility Considerations

The development and operation of icing facilities such as wind tunnels or engine test cells is covered under particular guidance such the SAE Aerospace Recommended Practice (ARP) 5905: Calibration and Acceptance of Icing Wind Tunnels [17], and it is recommended that tests on sRPAS icing are performed in facilities that have a calibrated flow field for both aerothermal and icing environments. If, however, such facilities are unavailable or the test requirements / operation mean that alternatives are required, there are a number of considerations that should be made when selecting / manufacturing test facilities.

- LWC should be measured (or derived) over the test area and the system calibrated to provide a range of conditions consistent with the icing requirements
- MVD should be measured and the system calibrated to provide a range of conditions consistent with the icing requirements
- Spray uniformity over the test area should be measured
- Drop residence time: sufficient distance should be set between the spray nozzles and the test articles to allow for supercooling of drops down to the ambient temperature of the surrounding air

8 Conclusions

8.1 Summary and Conclusion of Weather Analysis

Data provided by the European Centre for Medium-range Weather Forecast (ECMWF) Reanalysis v5 (ERA5) that offer atmospheric reanalysis of the global climate covering the period from January 1940 to present [11] have been used to asses potential RPAS icing conditions. For the present study, the weather conditions for a four-year period over a region with latitudes from 42° to 50° North and Longitude from 70° to 80° West have been analysed. This region was chosen to cover parts of the Ontario, Quebec and North Eastern United States and encompass the cities of Toronto, Ottawa, Montreal and Quebec City.

Unlike previous studies that have used ERA5 data to analyse the icing risk for RPAS, the work presented here has concentrated on the flight envelope relevant to sRPAS and therefore only weather conditions expected at altitudes up to 122 m (400 ft) have been considered. The analysis of the icing environment has been separated into two possible events, either potential encounters with clouds containing supercooled water drops (Appendix C or O) or with active precipitation such as snow and freezing rain.

The percentage likelihood of an icing encounter occurring has been assessed over the sample geographical area for individual winter months between October and April. This has shown, somewhat unsurprisingly, that snow and wet snow dominate the potential icing conditions over this region during the months of December, January and February. In addition, although small in comparison, instances of Appendix C and Appendix O (SLD) icing vary from a minimum of 0.33% (October) to a maximum of 1.05% (November) and suggest that the potential for an RPAS encountering these conditions should be considered as part of the demonstration of safe flight in icing. Similarly, mixed phase (rain/snow), freezing rain and ice pellets are all seen to contribute to the overall icing environment, with ice pellets becoming increasingly more prevalent in April at 1.57% likelihood.

When focusing on the particular icing conditions around the major cities, snow and wet snow are shown to dominate the weather conditions for Toronto, Ottawa and Montreal between December to February with this prevalence extending to November to March for Quebec City. Ottawa is shown to have the greatest likelihood of an Appendix C (or O) encounter during February whereas mixed phase (rain/snow) dominates the non-snow icing events for Toronto. For Quebec City, likelihood of mixed phase, freezing rain, ice pellets and Appendix C icing is seen to reduce during the central winter months (December to February).

The ERA5 data have also been used to quantify the intensity of particular icing events through use of the maximum precipitation rates available in the dataset. These data have been analysed to provide a relationship between precipitation rates and ground temperatures and has enabled a series of icing envelopes to be developed with the potential to form the basis of RPAS icing test criteria. Such an approach has the potential to assist in the development of operational practices and guidelines for sRPAS by industry standards organisations, such as the Society of Automotive Engineers (SAE), that define an sRPAS's ability to sustain safe flight in adverse conditions.

8.2 Summary and Conclusion of Icing Evaluation

A series of icing tests with sRPAS blades and full sRPAS have been conducted and compared to establish a means by which an applicant can demonstrate a system is capable of performing safe flight in icing.

Adverse weather conditions that may impact the safe flight of an sRPAS have been examined with the aim to define the icing threat and direct the development of test facilities that can simulate the appropriate environment. The icing environment related to the flight envelope of an sRPAS is as follows.

a) Appendix C Continuous Maximum. Defined by the airworthiness standard 14 CFR Part 25 Appendix C [9] for transport category aircraft, this specifies the icing environment relevant to the flight envelope of sRPAS and provides a range of LWCs related to particular MVDs and ambient temperatures. This envelope ranges from a maximum LWC of 0.8 g/m^3 at an MVD of 15 µm and ambient temperature of 0ºC (32ºF) down to a minimum LWC of < 0.1 g/m^3 at an MVD of 40 µm and ambient temperature of -30 ºC (-22ºF). The LWC values provided by the airworthiness standard are based on a horizontal extent of 17.4 nautical miles (20 statue miles), and a correction factor should be applied to the LWC to compensate for any difference between this and the expected travel of the sRPAS in the icing environment.

b) Appendix O freezing drizzle and freezing rain conditions are defined by the airworthiness standard 14 CFR Part 25 Appendix O [10] for transport category aircraft. Unlike the Appendix C envelopes, the LWC at a particular ambient temperature is based on four distinct drop size distributions for either freezing drizzle or freezing rain. These distributions are also separated into instances where the MVD is less than or greater than 40 µm. When defining the LWC for an sRPAS icing encounter, correction for an expected horizontal extent other than 17.4 nautical miles is required.
c) While both Appendix C and Appendix O envelopes define icing encounters in clouds, considering the flight envelopes of sRPAS, the threat of icing via active precipitation should also be examined. In particular, freezing rain precipitation should be considered as part of the icing assessment of an sRPAS, which (for the geographical region given in Figure 10) is seen to occur between +2°C and -19°C with a maximum precipitation rate of 8 L/hr m^2.
d) Other forms of precipitation, such as snow, wet snow, ice pellets and mixed phase, should be considered in the overall assessment of an sRPAS performance in icing; however, due to the lower risk of these precipitation types forming ice on the rotor blade, these are considered to be less of a threat to the aerodynamic performance of the vehicle.

Test have been performed on both single rotors in a calibrated icing cloud in a cold room as well as on full sRPAS systems in a winter environment. Having provided similar icing conditions in terms of temperature, LWC and MVD between the two test rigs, it was found that the time in icing at which the rotors could no longer sustain flight was equivalent for freezing drizzle and freezing rain conditions. Appendix C icing tests in the cold room overestimated the time to failure when compared to similar conditions for the full sRPAS. Tests performed in icing with a range of sRPAS showed markedly different responses to rotor performance degradation that varied from controlled landing through to sudden catastrophic failure in flight.

Considerations for performing icing tests for sRPAS have been provided and the steps an applicant would likely need to perform to demonstrate means of compliance for safe flight in icing have been detailed.

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