UAV ATMOSPHERIC ICING LIMITATIONS

CLIMATE REPORT FOR NORWAY AND SURROUNDING REGIONS

MAY 2021

UBIQ AEROSPACE
LEADING EDGE ATMOSPHERICS
THE NORWEGIAN DEFENCE RESEARCH ESTABLISHMENT

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MAY 2021

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EXECUTIVE SUMMARY

Atmospheric icing severely limits the potential use of unmanned aerial vehicles (UAVs)

The magnitude of this challenge is becoming increasingly clear with the increase of new and innovative use cases for UAVs, e.g., advanced air mobility. UAV manufacturers and operators must better understand atmospheric icing and newly available mitigation technologies in order to realize the business and technological potential of their aircraft.

Potential icing conditions generally occur with the presence of clouds and sub-freezing temperatures. As most UAV operations are performed from ground level up to 20,000 ft, temperature variations due to altitude could mean that an aircraft takes off in warmer temperatures, but still encounter icing conditions at the operational altitude. This is one of the explanations for icing being a global phenomenon, not one limited to the sub arctics, Arctic and Antarctic. When an aircraft flies into these conditions, water drops collide with the aircraft and freeze onto its surface. The most exposed elements to icing are:

- The airspeed sensor.
- The leading edge of aerodynamic surfaces.
- The propeller (for propeller-driven aircraft).

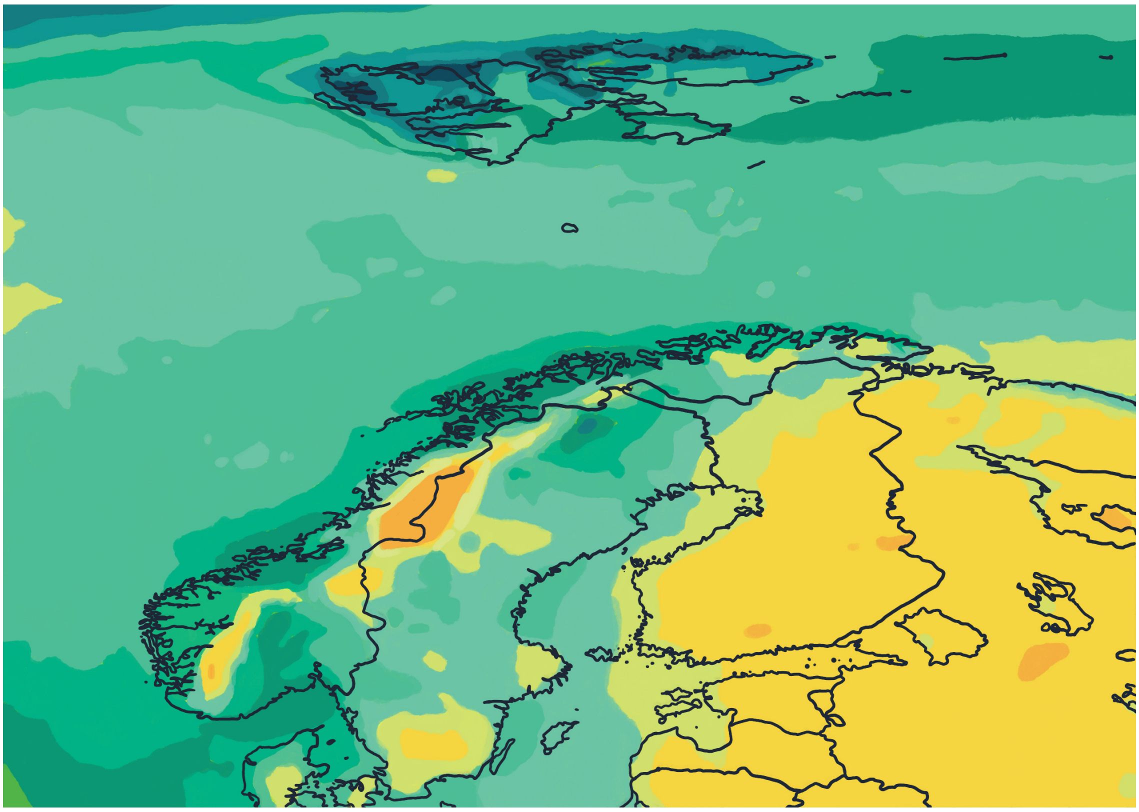
The operational implications of ice forming on these surfaces vary in nature, with critical malfunction of the airspeed sensor and severe performance degradation of the aerodynamic surfaces and propeller that can eventually lead to losing the aircraft. For UAVs, icing is significantly more hazardous than for manned aircraft, primarily due to the lower airspeed at which UAVs operate. The current mitigation actions related to UAVs are cancelling operations before they begin or terminating operations in progress.

A climatic analysis of the Norwegian airspace and surrounding areas has shown that large geographical areas in the region are exposed to potential icing conditions. *Figure 1* displays potential icing frequencies, the seasonal shifts in icing frequencies and implicitly highlights the gravity of icing as a UAV topic. The darkest red color depicted in certain areas in the second and fourth quarter signifies potential icing conditions frequencies from 90%-95%. Conversely, the light blue color seen in places in the third quarter indicates icing frequencies from 10%-15%.

From September through May, potential icing conditions are present from 35% to more than 80% of the time.

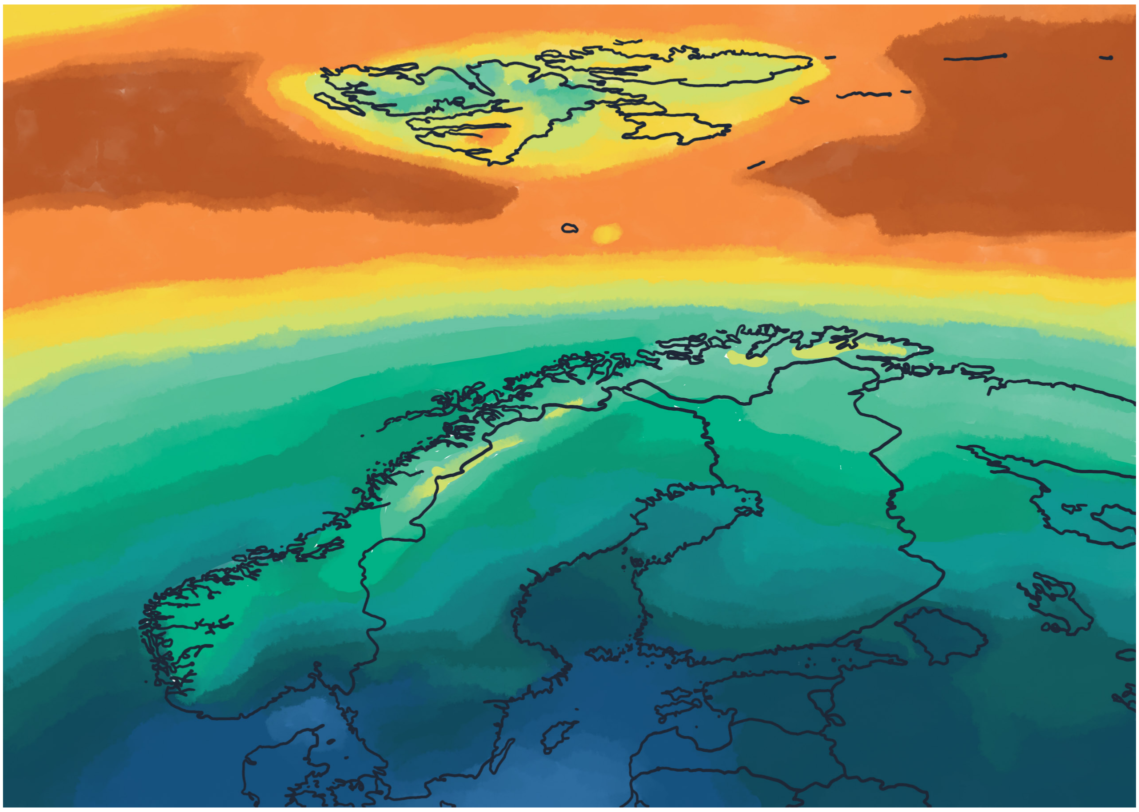
From September through May, potential icing conditions are present from 35% to more than 80% of the time, throughout the region of interest. For the remaining three months of June, July, and August, there is a slight decrease in the risk of icing condition, where some areas at times could experience as little as 10% other areas risk icing more than 50% of the time.

Figure 1 Showing potential for icing condition frequencies for the four quarters of the year – based on a climate analysis spanning data from the previous decade (2010-2019).



January
February
March

Surface - 30k ft



April
May
June

Surface - 30k ft

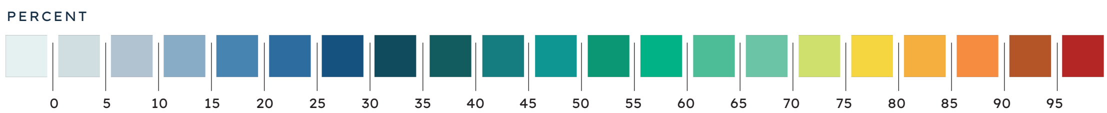
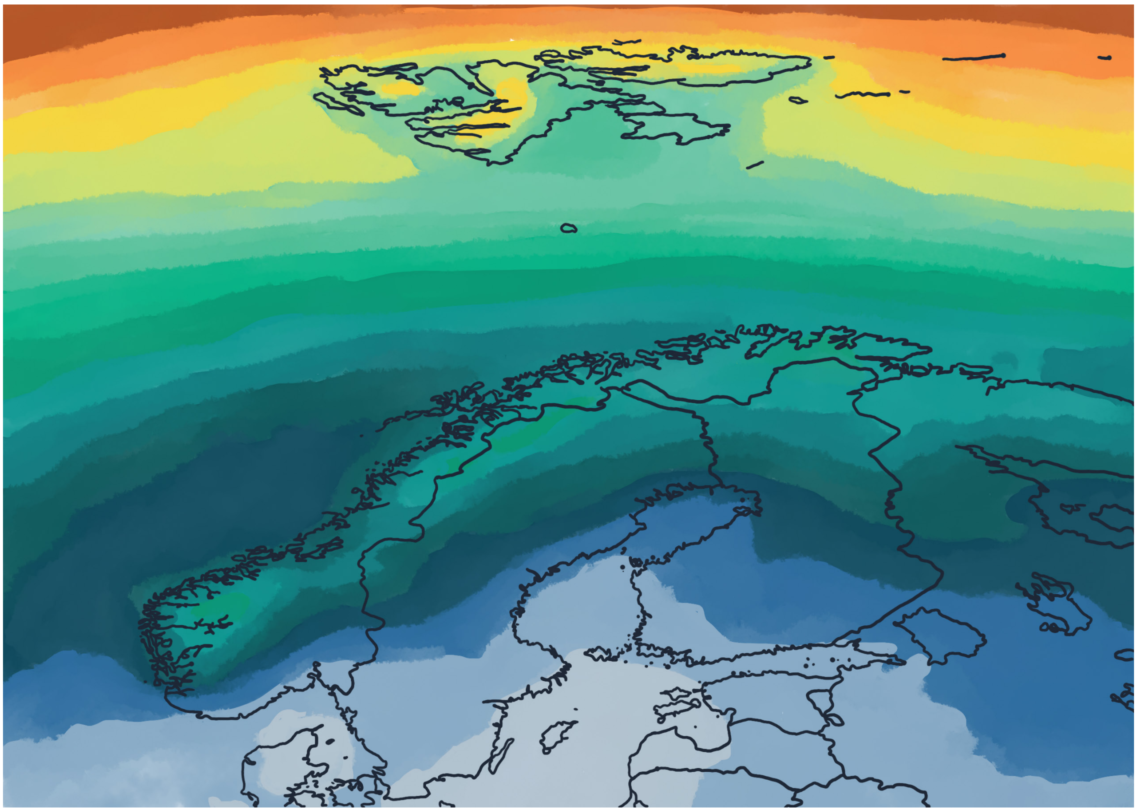
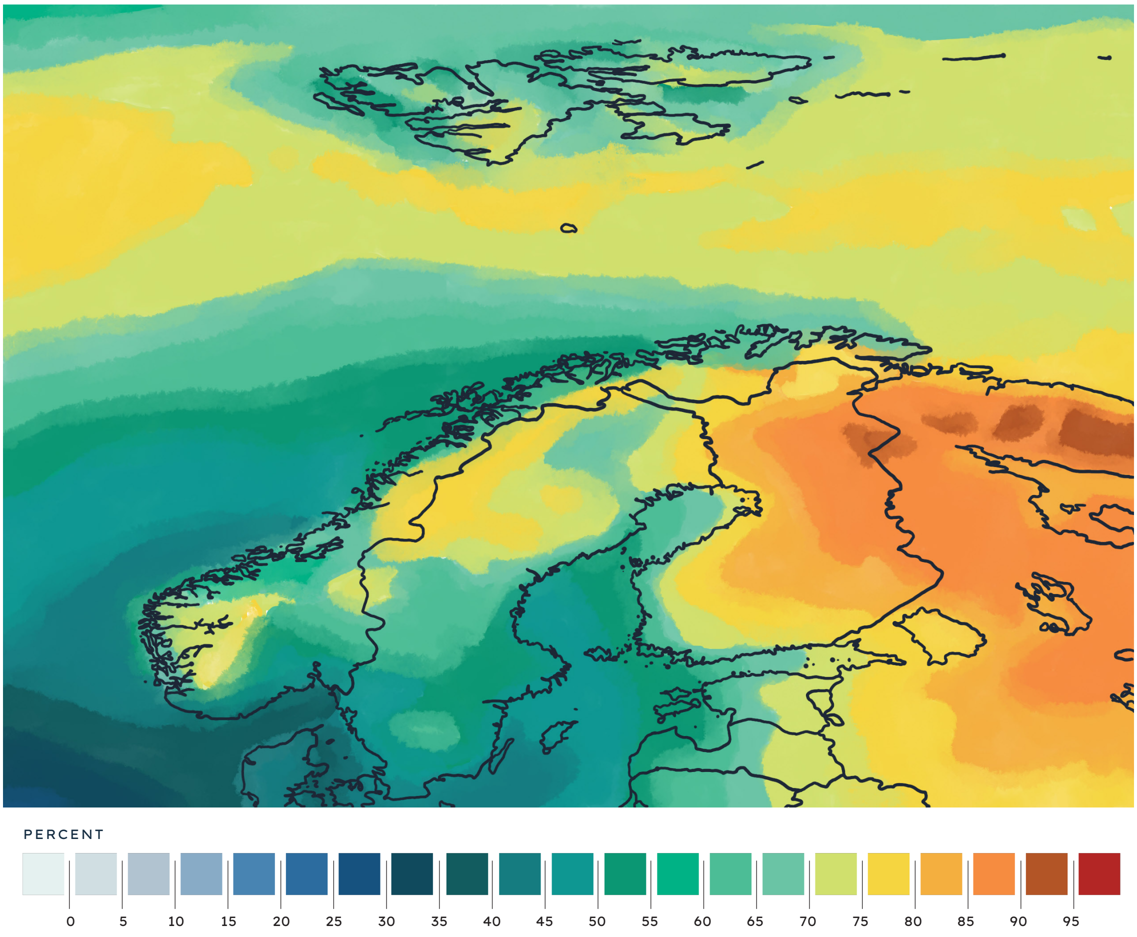


Figure 1 Showing potential icing condition frequencies for the four quarters of the year – based on a climate analysis spanning data from the previous decade (2010-2019).



July
August
September

Surface - 30k ft



October
November
December

Surface - 30k ft

EXECUTIVE SUMMARY

The implications for UAVs are severe. With the current icing mitigation method of simply not flying, UAV operations could be reduced or halted from 35% to more than 80% of the time during the spring, fall, and winter months. Potential icing conditions persist even into June, July, and August. Here, UAVs would not be able to operate from 10% to more than 50% of the time, depending on the specific time and location, all due to the risk of icing conditions.

For UAVs to be reliable and a valuable resource, the risk of icing must be addressed. Any solution must holistically address the various elements at risk. Ice detection sensor systems and airspeed sensor protection can provide UAVs with the means to initiate operations despite potential icing conditions. Ice protection for propulsion systems and aerodynamic surfaces is needed to enable capabilities for sustained operations when icing conditions are encountered. In combination, these systems can provide the reliability required for UAVs to be trusted and valued tools capable of performing critical and potentially life-saving operations.

Finally, civil aviation authorities will most likely require all-weather certifications for UAVs and AAM (advanced air mobility) aircraft looking to operate in urban and rural areas, as indicated by recent EASA and FAA publications. For manufacturers and service providers, this presents a challenge that will require focus and imminent action to ensure the utilization at the core of their businesses.

With the current icing mitigation method of simply not flying, UAV operations could be reduced or halted 35% to more than 80% of the time during the spring, fall, and winter months.

INTRODUCTION

This report is the first of its kind with a focus on atmospheric conditions at relevant altitudes for unmanned aerial vehicles (UAVs), other types of AAM (advanced air mobility) aircraft, and helicopters.

Modern-day UAVs and their use as, among other, reconnaissance vehicles were initiated by Israeli forces in the early 1980s. UAVs were used by the U.S. armed forces in the first Gulf War, and they came into public consciousness during the war in Afghanistan after the World Trade Center attack in 2001.[1] UAVs of the past and present were built for operating in the hot and humid conditions of the Middle East and Afro-Eurasia continent. Future UAVs will be deployed for global operations and missions, which presents new operational challenges that current day UAVs were never designed to overcome.

Icing is one of the most dangerous atmospheric phenomena for aircraft of all shapes and sizes. Assumptions regarding risks of icing being confined to operations performed in the Arctic or subarctic regions are common. This assertion may prove devastating as scientific studies have indicated that icing is a global phenomenon. The frequency of atmospheric icing is greater in cool regions. Still, when an aircraft or, more specifically, a UAV operates in cloudy conditions at operational altitudes with sub-freezing temperatures, that UAV is at risk of flying into icing. These conditions, clouds and sub-freezing temperatures at altitude, are not limited to any one region of the world. Therefore, it would be impossible to ensure the safety and reliability of UAVs performing critical activities unless the significant threat of icing is recognized and addressed.

In the context of this report, the moniker UAV includes autonomous and remotely piloted aircraft systems (RPAS) and encompasses both fixed-wing and multirotor aircraft.

OBJECTIVE

Quantify the risk of atmospheric icing as it relates to UAVs operating in Norwegian airspace and surrounding areas.

PURPOSE

Provide a substantiated reference document that enhances industry understanding of icing and the need for concrete safety requirements related to airworthiness certification for UAVs.

ATMOSPHERIC ICING

The term "atmospheric icing" relates to meteorological conditions wherein supercooled liquid water exists in the atmosphere. "Supercooled" refers to a state of water, where the temperature is below the freezing point while the water is in a liquid state. Supercooled liquid water occurs mostly in clouds (known as in-cloud icing) and sometimes in the form of precipitation (known as freezing rain or freezing drizzle). When an aircraft flies into these conditions, the water drops can collide with the aircraft and freeze onto its surface, see ***Figure 2***. This is called in-flight icing, and it is a hazard that can occur year-round on all types of aircraft,[2,3] all over the planet. There are three different types of ice: rime, glaze, and mixed ice (see ***Figure 3***).

Icing related to freezing precipitation is less common than in-cloud icing; however, it can be considerably more severe because water drops in precipitation are much larger than those in clouds. Thus, icing in freezing rain and freezing drizzle is called supercooled large droplet (SLD) icing; this can result in severe ice accretion, covering large surface areas with substantial penalties.

In-cloud icing and freezing precipitation are not the only icing hazards to aircraft. Frost occurs when a cold surface encounters warm and moist air. In this case, the water vapor forms a thin layer of ice on the cold surface (e.g., on a car windshield after a cold night). Ground icing refers to the accumulation of ice on an aircraft before takeoff. This form of icing can occur because of supercooled fog, frost, freezing precipitation, or snow, and it can be identified and addressed by appropriate pre-flight checks.

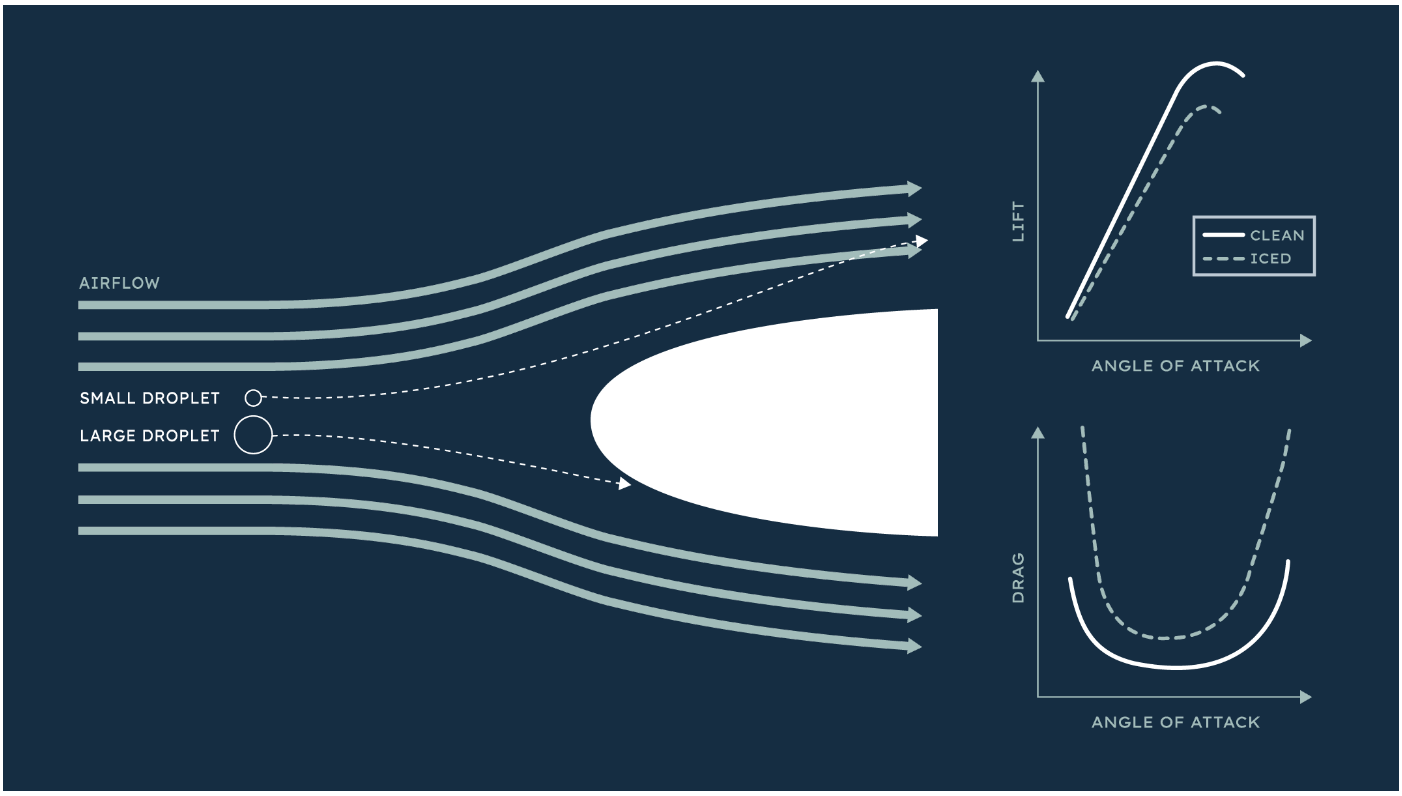
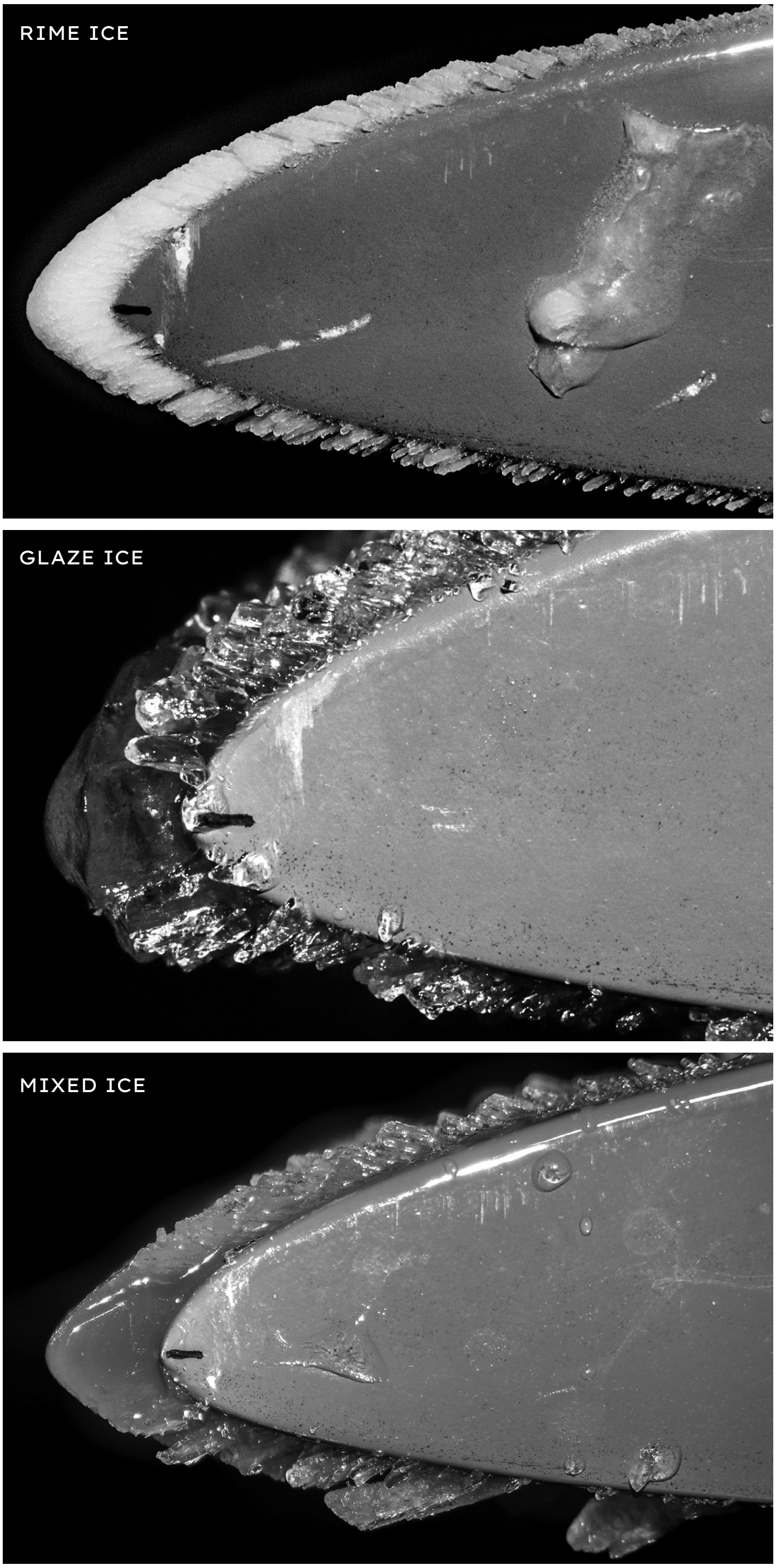


Figure 2 Small and large droplet behavior around an airfoil (left). Lift and drag curves of UAVs in clean and icing conditions (right).



Rime ice typically forms when the temperature of the droplets is so low (temperatures below -10°C), that they freeze instantly when they collide with a surface. During this process, small air pockets are trapped between the freezing droplets, which gives rime ice its characteristic white appearance. Rime ice shapes typically have a rough surface and a streamlined geometry that results in moderate aerodynamic penalties.

Glaze ice is also known as clear ice and it forms at temperatures near the freezing point (typically temperatures above -3°C). In this temperature regime, the incoming droplets do not freeze instantly but remain in their liquid phase for a longer period of time. The resulting liquid water film is gradually freezing on the surface and forms transparent ice shapes (comparable to ice cubes). Glaze ice shapes can form very complex geometries that can lead to severe aerodynamic penalties.

Mixed ice typically occurs in the temperature range between rime and glaze and is a combination of both ice forms. In mixed ice conditions part of the droplets that hit the surface freeze and parts remain liquid. The ice geometries that form during mixed ice vary considerably in shape and can lead to moderate or severe penalties.

Figure 3 Display ice shapes on a UAV airfoil.

ICING EFFECTS ON UAVS

When ice starts to accumulate on a UAV, it can affect three key aircraft systems. First, the most critical system with respect to icing is the pitot tube, which indicates the airspeed of the aircraft. Because of the small size of the pitot tube, it is very prone to icing and can clog up with ice quickly. A blocked pitot tube leads to erroneous airspeed sensor measurements, which is a severe hazard that has led to numerous crashes, for both unmanned and manned aircraft.[4]

Second, UAV propellers can accumulate large amounts of ice in a very short time, which can lead to substantial efficiency losses. Experimental and numerical studies show that UAV propellers can lose up to 70% of thrust within 2 min under icing conditions (see ***Figure 4***). Generally, UAVs are not capable of performing operations under such circumstances. Furthermore, ice can lead to increased mechanical torque and mechanical load on the motor. As a result of the high centrifugal forces, small ice fragments can be shed from the propeller blades. Ice shedding can lead to imbalances in the rotor dynamics and result in high vibrations that can damage the engine. The overall implications for propeller-driven UAVs operating in icing conditions, where ice builds on the propeller itself, rapidly converge towards unsustainable flight leading to a potential loss of the aircraft.

Third, ice accumulates on the aerodynamic surfaces of UAVs. The main concerns are the wings and the empennage. Ice accretions on these surfaces alter the geometric shape of the airfoils, which can lead to a decrease in their aerodynamic performance. When ice forms, the aerodynamic surfaces can generate less lift, more drag, and stall at lower angles of attack compared to that under regular operational conditions.

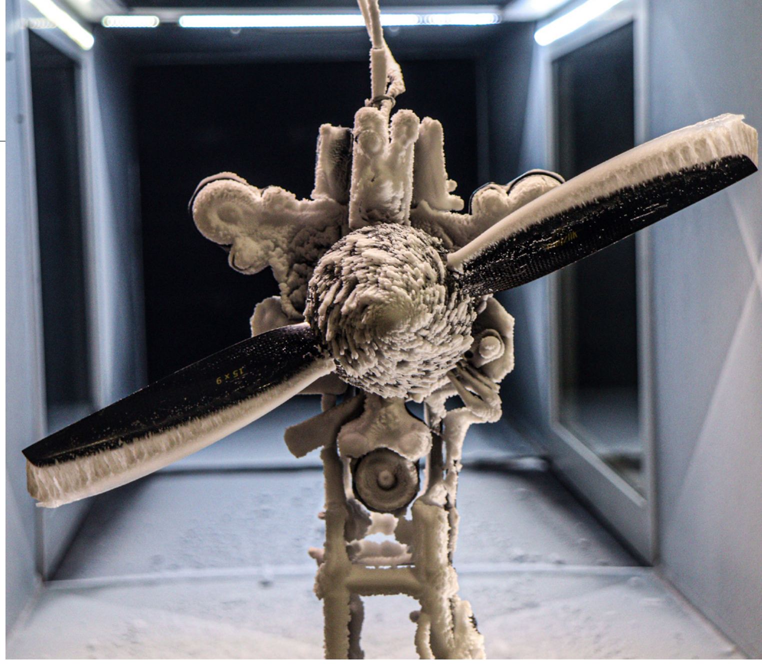


Figure 4A Propeller performance degradation in moderate icing conditions in an icing wind tunnel (right)

A numerical study found that in severe icing conditions, the lift was reduced by 35%, stall angle was reduced by 33%, and drag increased by more than 400%.[5] Furthermore, ice can affect the efficiency of flight control surfaces (aileron, elevator, and rudder). This negatively affects the controllability and stability of the aircraft. In addition, the ice mass that accumulates on the wings adds significant weight to the aircraft.

Icing may affect combustion engines by blocking engine inlets or by ingestion of large amounts of snow or ice. Further, engines without fuel injection are susceptible to carburetor icing; electrical engines are typically more robust against icing.

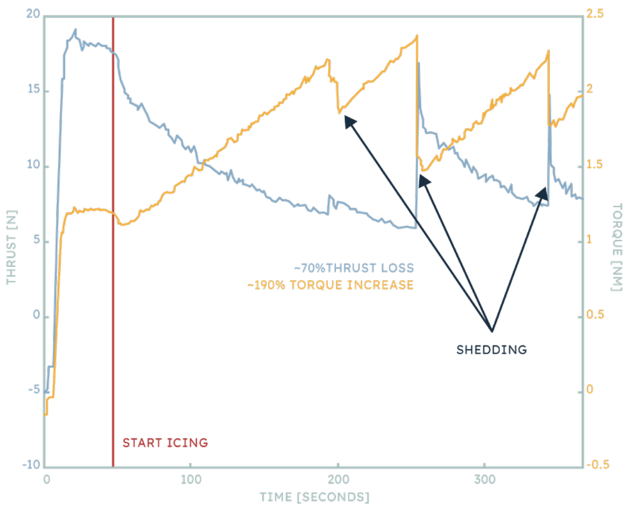


Figure 4B Propeller performance degradation in moderate icing conditions in an icing wind tunnel (right)

SPECIAL ICING CHALLENGES FOR UAVS

UAVs face several special technical challenges related to icing, and these are different from those for a manned aircraft.[6]

TYPE Icing effects and severity depend on the type of UAV. Rotary-wing UAVs are typically very sensitive to icing, making icing conditions a high risk. Fixed-wing UAVs are more robust in icing conditions; however, they are still at risk.

SIZE Small aircraft accumulate ice faster than larger ones because larger airfoils displace more air than smaller airfoils. The result is greater deflection forces on droplets, which means that smaller droplets do not impinge (see ***Figure 2***). In effect, small aircraft accumulate more ice per unit area compared to larger aircraft. Because UAVs are typically smaller than manned aircraft, they are substantially more sensitive to icing.

FLIGHT VELOCITY High airspeeds lead to aerodynamic heating on the wings and the propellers, which can counteract icing to some degree, especially at temperatures close to the freezing point. As UAVs operate at lower velocities than manned aircraft, they do not benefit from this effect. Therefore, icing can occur at a broader range of temperatures, including slightly subfreezing temperatures where supercooled water is the most common. Further, the high airspeed can exert substantial aerodynamic forces on ice accumulation and can cause the ice to fragment and subsequently shed. This ice shedding can significantly increase the efficiency of ice protection systems. Owing to lower airspeeds, ice shedding is substantially less efficient in UAVs compared to that in manned aircraft.

LAMINAR AIRFLOW The Reynolds number (a dimensionless number describing flow patterns) is approximately an order of magnitude lower for UAVs than that for manned aircraft. Consequently, UAVs operate in flow regimes where laminar flow effects are more prevalent than turbulent flow at high Reynolds numbers. Because laminar flow is more easily disturbed, the ice and surface roughness lead to higher penalties compared to that under turbulent flow.

WEIGHT UAVs are typically smaller than manned aircraft and have more stringent weight restrictions. Therefore, the added mass from ice accretions can quickly become problematic as the UAV may not be able to compensate for it, especially in addition to the aerodynamic penalties. Further, the additional weight can negatively affect the center of gravity, stability, and maneuverability of the aircraft.

SENSORS The most critical sensor concerning icing is the pitot tube that indicates the airspeed of the aircraft. Camera lenses, antennas, radomes, and other sensors can also be affected by icing, and this limits their functionality and adds weight to the aircraft. Furthermore, a sensor that can detect ice is necessary for UAVs because of the lack of an onboard pilot that can make visual observations.

AUTOPILOT & CONTROLS The autopilot is a critical system in UAVs, responsible for flight controls, navigation, path planning, take-off, and landing. In-flight icing changes aircraft flight behavior, and the autopilots of UAVs need to identify and adapt (e.g., increasing speed, reducing altitude, changing path) to this threat to ensure safe operation under all weather conditions. Autopilots available today are generally not designed with these capabilities.

CLIMATE ANALYSIS - ICING IN NORWEGIAN AIRSPACE

SCOPE

This study is based on meteorological data and forecasts collected over the last ten years.*

The data form the basis for an icing frequency analysis used to assess the climate conditions conducive to atmospheric icing and the frequency at which they occur in the Norwegian airspace and the surrounding regions. The findings of this study are translated in terms of the potential consequences for UAVs and those relying on their robust and safe operation.

* **January 2010–December 2019**

BACKGROUND

Data from the ERA5 (fifth generation ECMWF re-analysis) meteorological grids were used in this study. Over the past several decades, such “re-analysis” grids have been developed to provide consistent, gridded historical analyses of the state of the atmosphere across the globe. The term re-analysis refers to an optimized combination of meteorological observations and numerical weather model outputs. For the ERA5 grids, a 3D numerical weather model output from the European Center for Medium-range Weather Forecasts (ECMWF) based in the U.K. were combined with data from satellites, radars, surface stations, weather balloons, etc. Each of these datasets has been highly useful in the assessment of the presence of icing conditions, especially when used in combination. For example, satellite data provide essential information on the presence of clouds and their characteristics, including the presence of supercooled liquid water near the cloud top, while radars and surface stations provide critical information on precipitation presence, precipitation type, cloud height, and layering. For ERA5, the result is a high-quality combination of essential icing-relevant meteorological elements that provide a solid foundation for assessing the frequency of existence of conditions conducive to icing.

For this study, ERA5 grids of icing-relevant fields were examined for every 6 hours (00, 06, 12, and 18 UTC) at 31-km/0.25° grid spacing described above, covering the years from 2010 to 2019 (the most recent complete decade of data). Six-hourly grids were selected as a compromise to balance the dataset size while examining datasets that represent all portions of the day and night. The raw fields used include vertical columns of pressure, geopotential height, temperature, relative humidity with respect to water, cloud coverage, and surface precipitation rate valid at ground level.

The findings of the climate analysis form the basis for the conclusions of future icing consequences in this report.

ICING ASSESSMENT AND FINDINGS

There are many approaches to divide and visually represent the ten years’ worth of data, which forms the basis for this report. The report focuses on providing a general overview of the atmospheric icing conditions over the Norwegian domain. A few selected plots were used to reflect this.

Before presenting the resulting frequency maps, it is necessary to explain how they are developed and what they represent. The results are based on estimating the likelihood of icing conditions using the ERA5 data set. Using an algorithm (ICE3D) developed by research meteorologists at Leading Edge Atmospherics, the likelihood for icing is calculated at every 3D data point in the grids over this period. The likelihood value, which ranges from 0.0 (icing is not expected) to 1.0 (icing is highly likely), is determined based on atmospheric parameters that are indicative of icing conditions described above, including cloud coverage, temperature, relative humidity, and vertical structure.

A simple threshold is used to determine icing likelihood values sorted into either “icing” or “no icing.” The selected threshold reflects conditions under which the UAV may be grounded, that is, when clouds and/or precipitation are likely to be present, and temperatures are in the range where a risk of icing exists.

From the ICE3D results, the frequency of the conditions mentioned above (0–100%) is determined for each location and mapped across an area of interest. Therefore, a frequency value of 0% indicates that the potential for icing on a UAV is essentially zero. In comparison, values approaching 100% indicate that conditions conducive to icing are extremely likely to be present, which could inhibit safe UAV operation without ice protection.

FULL-COLUMN MONTHLY FREQUENCY MAPS

The following frequency maps (***Figure 5***) represent the percentage of time for each month, where the mapped areas had potential icing conditions based on the ICE3D algorithm and the selected threshold. The chart shows the icing frequencies for the complete operational airspace from the ground level to 30,000 ft. The estimated icing conditions in any of the altitude bands result in the entire height column being identified as having icing conditions for the corresponding 6-hour data point grid.

The color chart in ***Figure 5*** signifies the amount of time, in percent, where potential icing conditions are present for each of the twelve months. An area identified by white would have a 0% likelihood of possible icing conditions in that specific month. Conversely, an area marked by red would have a more than 95% likelihood of potential icing conditions throughout that month.

Over a year, the lowest potential icing frequencies are found in the south of Norway in July. In the area along the coast around Kristiansand, potential icing conditions exist from 10-15% of the time. In July 10-15% translates into three to five days where UAVs could be grounded due to these conditions. For the rest of Norway, higher frequencies are prevalent during the month of July. For a region stretching from Bergen in the west towards the Swedish border to the east, encompassing the greater Oslo area, potential icing conditions are prevalent from 20-30% of the time (six to ten days of potentially grounded UAV operations in July). In much of mainland Norway, potential icing conditions exist from 30%-60% of the time. In select areas, potential icing conditions are present more than 70% of the time over a year. The same areas are susceptible to potential icing frequencies peaking at 95% at specific times in the period from October through May. For UAVs, a likely implication is grounded operations for more than one hundred days in those eight months. At most, operations will be grounded up to two hundred and twenty days in the same period.

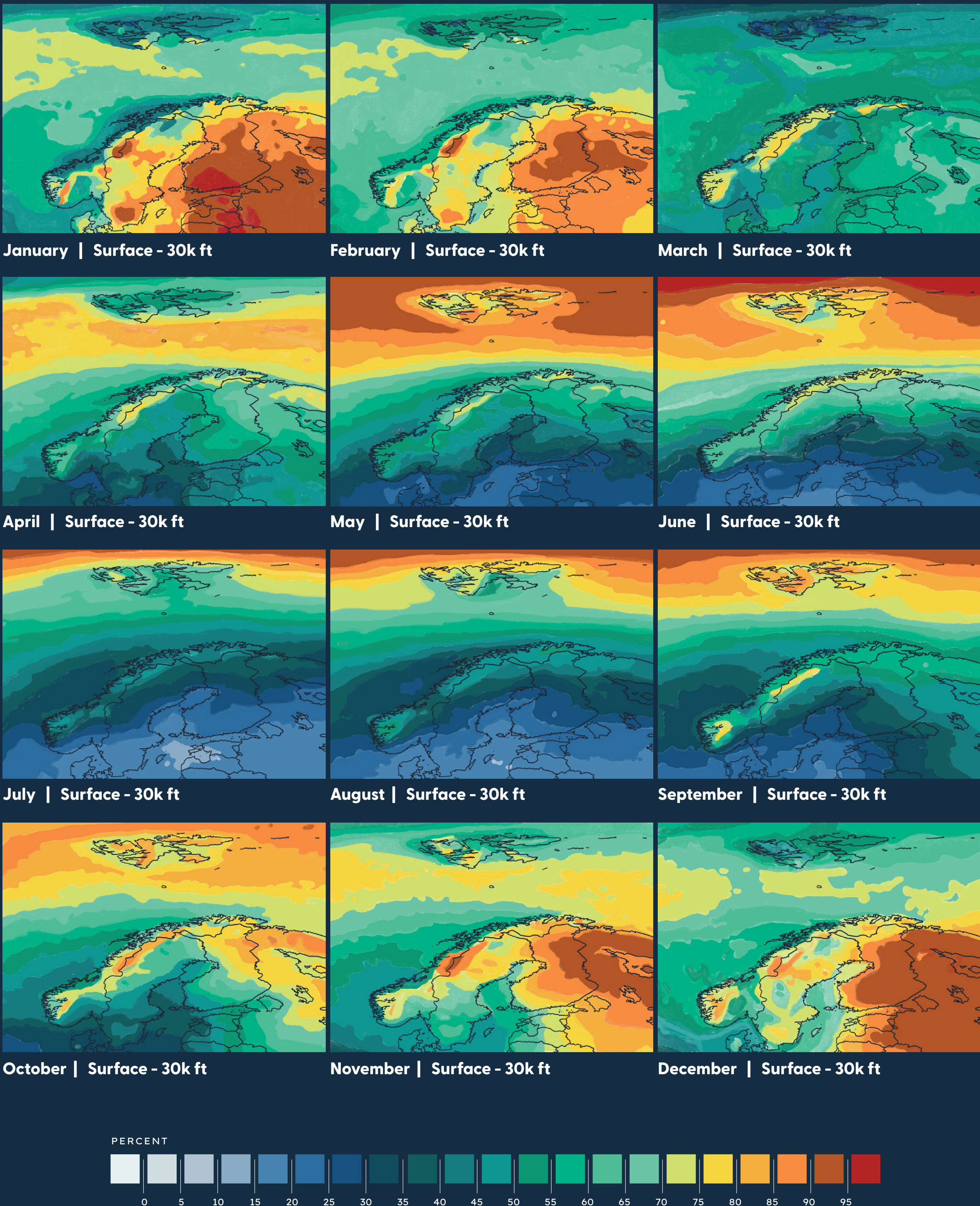
Figure 5 shows that high icing frequencies are evident over significant portions of the map, including over southwestern Norway and the Norway–Sweden border. The high frequencies found along the border during the cold season are likely associated with the upslope lift, which often results in subfreezing clouds with a high risk of icing.

In much of mainland Norway, potential icing conditions exist from 30%-60% of the time.

The icing patterns are reasonably similar across Norway, where higher frequencies are found in elevated terrain areas. Lower frequencies are located just off the west coast, and they increase further offshore and towards the north. The relative minimum found off the coast of Norway is presumably attributed to the cool sea surface temperatures associated with the Norwegian Coastal Current, which causes a localized decrease in the maritime cloud cover and a drop in the icing frequency.

Figure 5

Displaying the potential icing frequencies for each of the twelve months for Norwegian airspace and surrounding areas.



As shown in ***Figure 5***, many month-to-month geographic shifts in the icing frequency appear to be minimal. However, the seasonal changes are more clearly visible. For example, peak icing frequencies are concentrated toward the south of the Norwegian domain in January and December, when the temperatures are ideal for icing. By April, the icing maximum shifted northward to become more heavily concentrated between mainland Norway and Svalbard. The maximum continues its shift northward to reach Svalbard in May–June, and then, it passes to the north of Svalbard in July and August. After the warmest part of the summer, this pattern reverses. The maximum frequency area shifts southward, reaching Svalbard in September and October, and it becomes more strongly evident again in and around mainland Norway's elevated terrain. The southward shift continues during November and December, with frequencies further increasing over and around the elevated terrain.

The icing frequency tends to be greatest on the western side of the elevated terrain of southern Norway. Interestingly, to the east of the highest terrain, a downslope shadow effect materializes with a lower frequency of icing. This low-frequency area appears to encompass the greater Oslo region and a sizable area to the northwest of the city. The relative maximum along elevated terrain appears to be more static through spring into summer compared to other areas of the domain that drop off more precipitously. This is attributed to a change in the dominating icing mechanisms from the upslope icing to a mix between both upslope and convective icing during the warm season.

In the northernmost part of inland Norway, there is a local maximum of icing frequencies around the elevated terrain toward the Swedish border. The area with the greatest icing frequency during the cold season is the upslope side of the less steep high terrain along the central Norway–Sweden border, which is essentially uphill from Trondheim, Brønnøysund, and Bodø.

The Svalbard region generally has relatively high icing frequencies throughout a large fraction of the year. In contrast to mainland Norway, the icing frequencies peak between May and October, rather than during the heart of the cold season.

TIME-HEIGHT FREQUENCY MAPS

This section presents plots of inferred icing condition frequencies across the year over the operational airspace for eight different locations of relevance in Norway. The results were divided into altitudinal bands. The time-height frequency maps add an extra dimension to the icing likelihood analysis compared to the full-column month frequency maps. They provide insight into how icing tends to be distributed vertically and how icing altitudes change throughout the year. The selected locations are: (1) Rygge, (2) Oslo-Gardermoen, (3) Dagali, (4) Bergen, (5) Ørland, (6) Andøya, (7) Bardufoss, and (8) Tromsø.

The approach used to generate the time-height frequency results follows the same methodology as that presented for the full-column month frequency maps; the vertical dimensions are separated into altitude bands. The lowest layer of the time-height frequency plots is the surface-to-1,000 ft-above-ground-level (AGL). This specific layer is indicated on the horizontal axis and signify particular importance for UAV operations. The remaining series of altitudes are altitude bands relative to mean sea level (MSL), where different subsets of UAVs are operated.

Considering the time-height frequency map of Rygge (***Figure 6***) and Oslo-Gardermoen (***Figure 7***) that share similar icing patterns, the icing frequencies are maximized at relatively low altitude bands during the coldest winter months. During spring and summer, icing frequencies decrease, and icing altitudes increase. This is attributed to the general increase in temperature and the moisture being focused in higher altitude bands. The trend is then reversed in the local fall season, thereby forming a pattern for the year that resembles an inverted “C.” From the ground-to-1,000 ft MSL, the icing conditions are not expected from May until September, because temperatures rarely drop below 0 °C. However, above the 1,000 ft MSL, the risk of icing still exists, even during the local summer months.

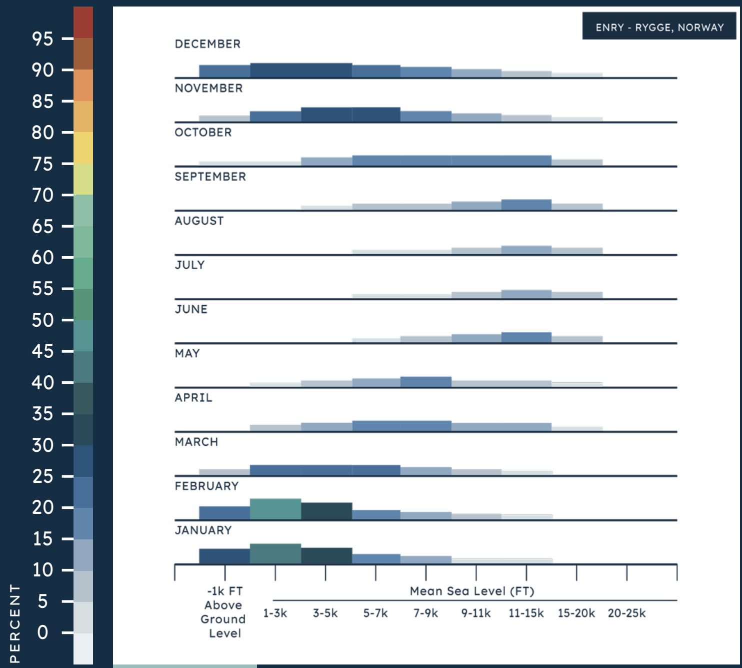


Figure 6

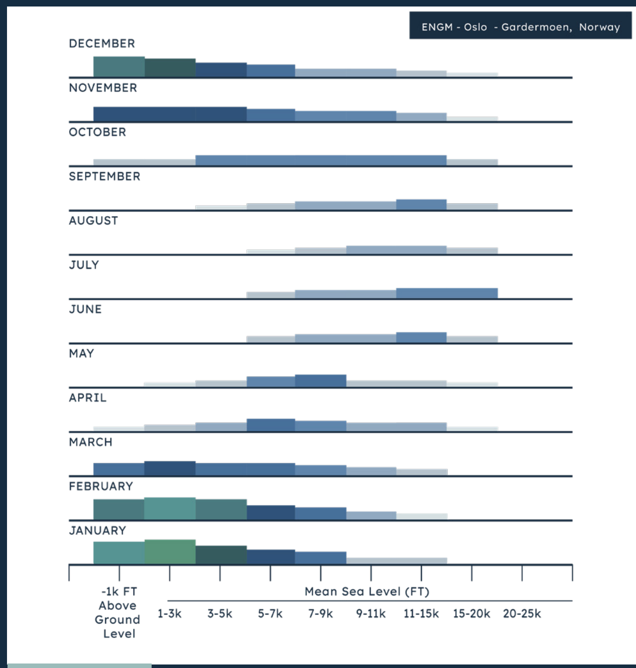


Figure 7

Along the southwestern coast, Bergen (***Figure 8***) maintained a similar shape to those found at Rygge and Gardermoen. However, the peak values are now centered around the 3,000–7,000 ft MSL band during the local colder season months, which is slightly higher than that of Rygge and Gardermoen. This is likely due to Bergen’s marginally warmer climate. Dagali, located in the elevated terrain between Bergen and Oslo, exhibits behavior closer to Gardermoen but with slightly higher frequencies in the 3,000–7,000 ft MSL band (see ***Figure 9***).

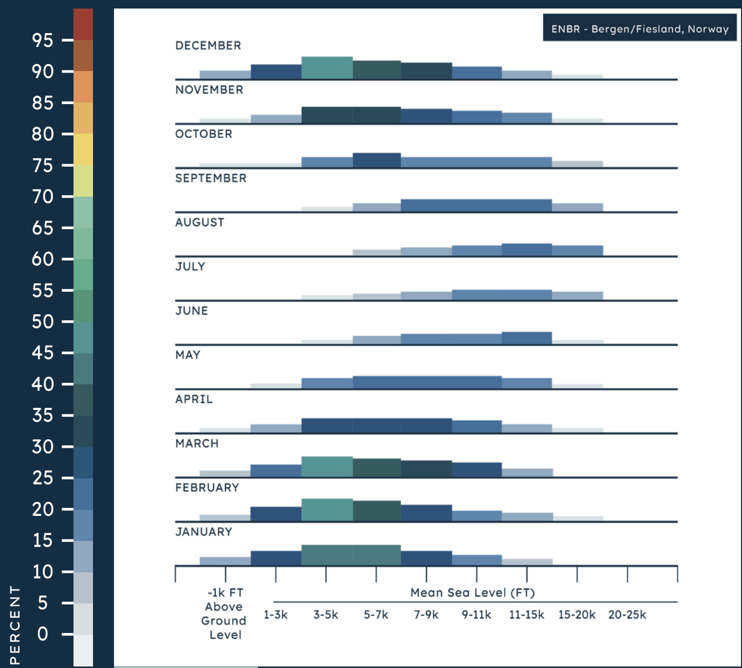


Figure 8

Figure 9

Along the west coast, Ørland maintains the inverted "C" pattern, as seen at Rygge, Gardermoen, and Bergen (see ***Figure 10***). However, for Ørland, the peak icing frequencies were slightly lower. Similar to Bergen, the overall maximum frequencies are found at the 3,000–7,000 ft MSL band, and near-ground-level icing patterns are comparable.

Patterns and overall frequencies are similar further to the northeast along the coast at Bodø (***Figure 11***). The near-surface frequencies are somewhat larger (20–30%), and the maximum frequencies are broader and continue further into the local spring and fall. The peak frequencies exceeded 40% over nearly half the year.

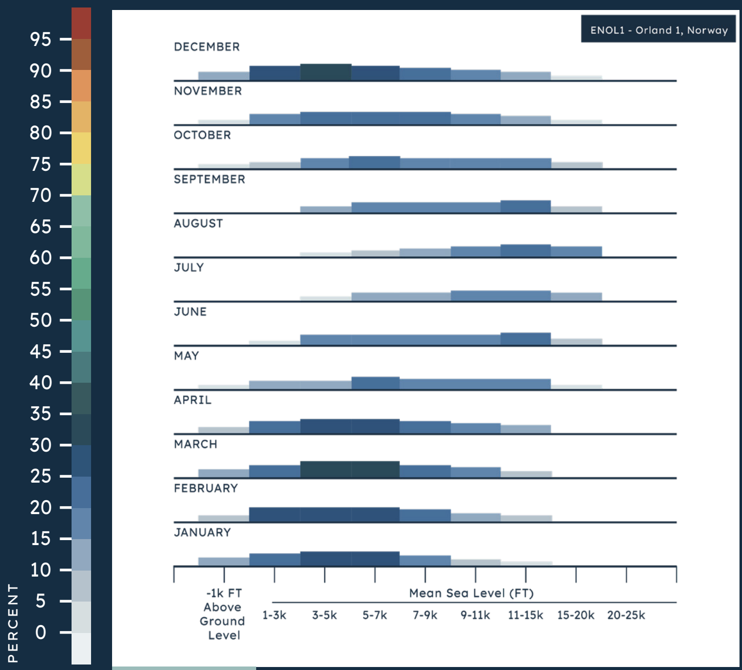


Figure 10

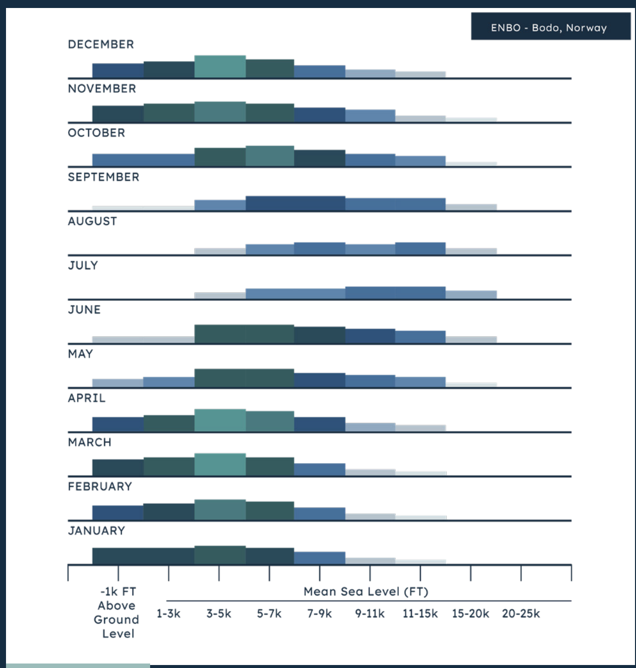


Figure 11

Even further northeast, Bardufoss and Tromsø have icing maxima that are even broader than those for locations further south, running from October through June, with some reduction in the local summer (see ***Figure 12*** and ***Figure 13***). The inverted "C" shaped icing pattern is slightly more compressed with increasing latitude. The small local summer maximum is more constrained in terms of duration, and it only briefly reaches altitudes above 15,000 ft MSL with more than 10% frequency. Meanwhile, the ground-level icing maximum is similar to that of Bodø, with peak frequencies of 30–45% between November and March.

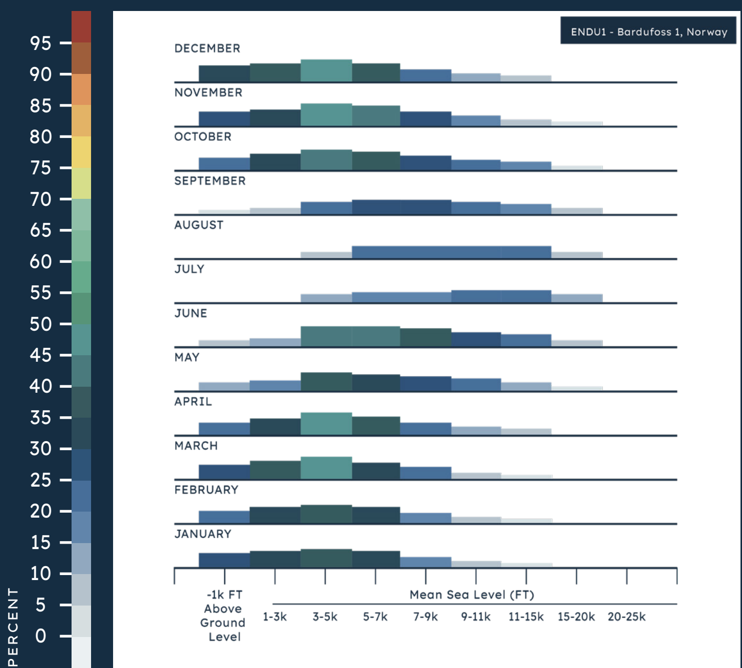


Figure 12

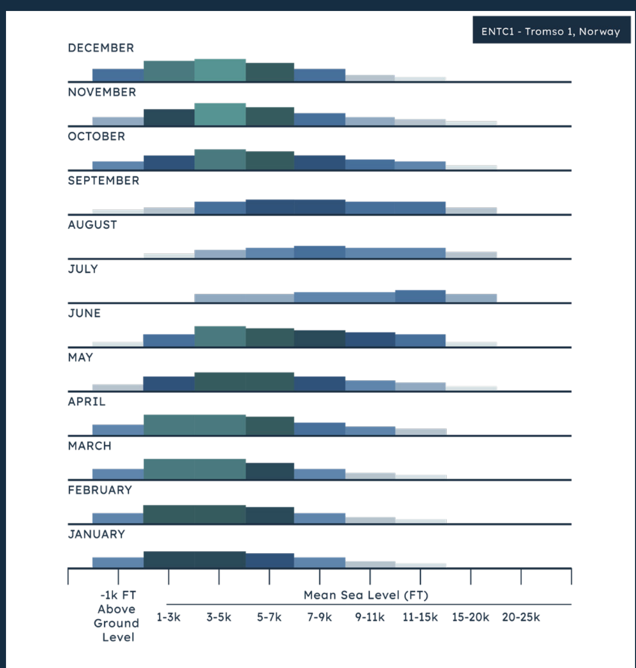


Figure 13

ICING CONSEQUENCES FOR UAV OPERATIONS IN NORWAY

MISSION CRITICALITY OF ICING

UAVs are relied upon in the Norwegian Armed Forces to provide critical capabilities. For example, they are increasingly used as integral assets in complex military operations, and they aid in local and theaterwide situational awareness (SA) building and targeting. Numerous other applications are emerging, including communications and logistics services.

Owing to significant, location-dependent, and currently unpredictable weather restrictions, the availability of UAV-provided services is less than desired. This affects the ability to attain information superiority by using flexible and responsive airborne sensors, and therefore, it affects the operational tempo and increases risk.

Weather restrictions on military UAV availability stem from both actual vulnerabilities to icing and wind, and from procedural risk mitigation, where the largely unknown actual risk is met by imposing significant safety margins; for example, flying in clouds/fog or precipitation at cold temperatures is largely avoided.

UAV operators assess the weather conditions during mission planning and flight using a combination of meteorological services, qualitative understanding of the general weather scenario, knowledge about local terrain, and observed local weather conditions. No mature and sophisticated UAV specific weather services are currently available. The available weather services are adapted to the needs of the public and manned civilian and military aviation. Current UAV systems generally lack the ability to mitigate risk (e.g., through path planning, cloud, and ice detection) and operate in icing conditions (using anti- and de-icing). This leaves UAV operations with large and unquantifiable risks that are dealt with by using large safety margins, the extent of which depends on the operational scenario and the given aircraft. The consequences of (unpredictably) reduced UAV availability may be severe depending on the application/mission type. One important consequence is that the potential for UAV employment remains underexploited.

One important consequence of icing is that the potential for UAV employment remains underexploited.

The findings of this report provide an impression of the reduced availability and risk caused by icing, and this is expected to motivate further developments in air vehicles and supporting systems and services.

MITIGATING ICING FOR UAVS

Four different ice protection systems are necessary to protect UAVs from the adverse effects of in-flight icing fully.

1. First, a UAV must be able to detect the presence of icing conditions. Ice detection sensors infer the presence of icing conditions using a wide range of physical phenomena. For example, sensors can detect ice on the aircraft's surface by determining the optical, mechanical, electrical, or thermal effects. Another method to detect icing is to monitor flight performance data such as lift, drag, thrust, and torque. Using intelligent algorithms and artificial intelligence methods, the degradation of these parameters can be used to infer the icing conditions. A UAV equipped with this type of sensory system would be capable of initiating operations despite the presence of potential icing conditions. If icing is encountered during operations, the sensor system provides an early warning enabling a pilot or the autopilot to escape the hazardous conditions and, if necessary, return to the ground.

2. The second system that needs protection against icing is the pitot tube, which is a type of airspeed sensor. Some ice protection approaches have been developed because pitot tubes are susceptible to icing. One such approach is the heated pitot tube, which applies an electrothermal method to ensure that the pitot tube maintains an internal temperature above freezing when an aircraft flies into potential icing conditions. Protection of the pitot tube provides value comparable to that of the ice detection systems, as it is required to escape icing conditions and return to the ground if needed.

3. The propulsion system and lifting surfaces (i.e., wings and empennages) are the third components that need to be protected against icing. While several different types of ice protection systems are available for the protection of lifting surfaces of manned aircraft, there are only a few mature technologies for UAVs. These critical surfaces can be protected using electrothermal heating systems, weeping wings that disperse a freezing point depressant, or mechanical systems that remove ice with vibrations or displacement. Ice protection for propulsion systems and lifting surfaces provide value by enabling sustained operations even when icing conditions are encountered.

4. Finally, appropriate mission planning tools are required to assist the safe operation of UAVs in icing conditions. Such tools need to consider meteorological weather forecasts and identify the icing risk for each mission. Aircraft trajectories should be optimized to weather patterns and conditions, including icing risks and icing penalties. An optimized path planning will maximize operational output, especially when a UAV is faced with icing conditions.

FINAL NOTE

SUMMARY

This report has quantified the risk of atmospheric icing to unmanned aerial vehicles (UAVs) operating in the Norwegian airspace and the surrounding areas. The basis is an assessment of climate conditions conducive to icing and the frequency at which these conditions occur in the mentioned region.

A review of atmospheric icing, its potentially severe consequences and associated implications for UAV operations, and the regional scale of this threat has been presented. This review and presentation are followed by the climate analysis itself, where publicly available climate data is used to estimate the frequency of conditions conducive to icing. The analysis results indicate high frequencies of conditions conducive to icing all year round, where large geographical areas are exposed to a more than 50% icing risk from October through February, i.e., a typical UAV would only be capable of operating less than 50% of the time.

For UAVs, the most likely implication of potential icing conditions over the entire year is grounded operations for more than one hundred days. At most, operations could be grounded up to two hundred days.

The climate analysis includes a focused presentation of time-height icing frequencies, i.e., a display of icing risks year-round at various altitude bands. From the eight focus areas presented, it becomes evident that the risk of icing is predominant at altitudes from ground level to 10,000 ft and a continued significant presence up to 20,000 ft during the warm season in certain areas.

For UAVs to be a reliable and valuable data gathering tool, the risk of icing needs to be mitigated. Specifically, a holistic solution combining different systems are required; ice detection sensor systems and airspeed sensor protection provide UAVs with the means to initiate operations despite the presence of potential icing conditions; ice protection for propulsion systems and lifting surfaces provide value by enabling sustained operations even when icing conditions are encountered.

OUTLOOK

This report is the first of its kind with a focus on atmospheric conditions at relevant altitudes for UAVs, other types of AAM (advanced air mobility) aircraft, and helicopters. In the current environment of expanding UAV applications for Defense, governmental, and enterprise purposes, the report offers unique insights and highlights a significant inhibiting factor to growth in multiple industries. The novelty of the analysis presented in this report has revealed a need for further investigations of similar character in specific and relevant regions elsewhere. Input from stakeholders will be sought as a guide to areas of interest ranging from strategic to rural and urban. The following lists the expected focus areas of the coming years.

- The Arctic and northern Europe – e.g., Greenland, Iceland, and Denmark.
- North America – e.g., the great lakes area and Alaska.
- Europe – e.g., Germany, France, and Spain.
- Asia – e.g., India, China, and Japan.

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APPENDIX

BIOGRAPHIES

AUTHORS

Dr. Kim Lynge Sørensen is one of the founders and the CEO of UBIQ Aerospace. Originally from Copenhagen, Denmark, he has a M.Sc. in electrical engineering with a special focus on robotics from the Technical University of Denmark (DTU) and Stanford, CA, US. In 2014 he joined NASA Ames Research Centre as a visiting researcher, working on an autonomous icing protection solution for UAVs (unmanned aerial vehicles) as part of his doctoral studies. In 2016 he was rewarded with a PhD in Aerospace Cybernetics from the Norwegian University of Science and Technology (NTNU), and in 2017 he became one of the founders of UBIQ Aerospace. In 2018, after 2 years as a post-doctoral fellow at NTNU AMOS, he officially joined UBIQ in the position he still holds as CEO.

Dr. Kasper Trolle Borup is one of the founders and the CTO of UBIQ Aerospace. Kasper, who is from Copenhagen, Denmark, has a MSc. in electrical engineering with a special focus on robotics technology from the Technical University of Denmark (DTU) and Stanford, CA, US. In 2014 he joined NASA's Jet Propulsion Laboratory as a visiting researcher working on navigation systems for micro aerial vehicles intended for missions on Mars. In 2017 he was part of a small group who founded UBIQ Aerospace. 2018 he was awarded a PhD in Aerospace Cybernetics from the NTNU, and in 2019, after a year as a post-doctoral fellow at NTNU, he joined UBIQ in the position he still holds as CTO.

Dr. Richard Hann holds a degree in aerospace engineering from the University of Stuttgart in Germany. He completed his PhD on the topic of icing on UAVs at the Department of Engineering Cybernetics of the NTNU in 2020. The same year Richard was the lead author on the research report "Unsettled Topics in Unmanned Aerial Vehicle Icing" commissioned by SAE International. Today, Richard one of the leading researchers in the field of UAV icing and also works as lead aerodynamics engineer at UBIQ Aerospace.

Ben C. Bernstein is a meteorologist who has specialized in aircraft icing for more than 30 years. As a researcher, he has studied mechanisms that cause icing to form, intensify and dissipate, supported numerous NTSB investigations of icing-related accidents, led the development of NOAA's operational icing products, and produced a large number of publications, including studies of the production of large drop icing and the climatology of icing. As a consultant, Ben works with the FAA on the development of new icing tools for the terminal area, develops training materials for meteorologists and pilots, and works closely with dozens of aircraft manufacturers around the globe, guiding their test aircraft into conditions needed for certification.

Morten Hansbø is a Principal Scientist at the Norwegian Defence Research Establishment and has a master's degree in Physics and Mathematics. He has nearly 20 years of experience with unmanned systems. He has also worked with anti-aircraft missile systems in the Norwegian Armed Forces. Hansbø has taken a special interest in contributing towards greater usability of unmanned aircraft in the Nordic and Arctic Region.

REVIEWERS

Dr. Peter W. Webley is the Associate Director of Research for the Alaska Center for Unmanned Aircraft Systems Integration (ACUASI) and a Research Associate Professor of Remote Sensing, Geophysical Institute, University of Alaska Fairbanks. Dr. Webley has a PhD in Remote Sensing and more than 15+ years of experience as a geoscience and remote sensing scientist and researcher. He worked on the development of operational and real-time applications of geospatial data for hazard detection and decision making. Dr. Webley studies remote sensing of natural hazards, dispersion modeling of aerosols, satellite detection methodologies, the application of unmanned aircraft systems for geoscience research and operational support, scenario planning for natural hazard assessment and risk mitigation, 3-D visualization of aerosol modeling, business development, technology transfer, and entrepreneurship.

Ben FitzGerald is a partner at Lupa, a private investment firm, and an adjunct senior fellow at the Center for a New American Security (CNAS). At Lupa he leads the firm's investment portfolio for technology with broadly defined security implications. At CNAS, Ben continues to speak and write on the intersection of strategy, technology, and business as they relate to national security. Prior to these roles, Ben was the Executive Director - Strategy, Data, and Design in the Pentagon's Office of the Undersecretary of Defense for Acquisition and Sustainment. Here, he was the lead official responsible for reorganizing the former office of Acquisition, Technology, and Logistics. Before the Pentagon, Ben was a Professional Staff Member on the Senate Armed Services Committee. He also served as the Director of the Technology and National Security Program at CNAS, the founding Managing Director for the North American business of Noetic, a strategy consulting firm, and worked in a number of technology corporations to include IBM and Unisys. Ben has written legislation, defense acquisition policy, including the creation of new acquisition pathways and governance models, and a variety of think tank reports. He has testified before Congress and his commentary has appeared in Defense News, Foreign Policy, NPR, Reuters, Vice, and on C-SPAN.