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Icing Impact on UAS and AAM Operations in Selected US Metropolitan Areas

An icing climate assessment for Los Angeles, San Francisco, Chicago, and New York

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1 Executive Summary

The advanced air mobility (AAM) industry holds the potential to revolutionize urban and regional transportation, drastically reducing travel times, operating emissions, and congestion. However, several challenges need to be addressed before we get to see the full potential of AAM.

One of these challenges is atmospheric icing. This report details the problem of atmospheric icing and the specific challenges this phenomenon will pose for AAM aircraft. To assess the impact of icing, the report contains a climate study of four relevant US metropolitan areas: *Chicago, New York, San Francisco, and Los Angeles.*

When an aircraft enters atmospheric icing conditions, supercooled water droplets collide with the aircraft and freeze on the surface. This leads to a gradual accumulation of ice on critical surfaces and sensors. The resulting ice accretion causes significant performance degradation of the aircraft's aerodynamics and/or a malfunction of relevant sensors or systems. These icing impacts, If unmitigated, can easily lead to a loss of aircraft.

Compared to traditional aviation, the threat from icing can be even more pronounced for AAM aircraft due to their size, low flight velocity, and operational envelopes.

Out of the four metropolitan areas covered in this report, Chicago is most frequently affected by icing. Due to the cold temperatures during the winter months and the fact that moisture is often plentiful in the Great Lakes region, icing is frequent during the cold season, with peak frequencies at lower altitudes of below 5.000 ft (*all heights MSL, unless otherwise specified*). In the months from November to February, icing frequencies from surface to 15,000 ft are above 50%, reaching values as high as 60–75%. During these months, icing tends to peak between 4 am and 10 am in the day at local Chicago time in the hours surrounding sunrise.

New York has higher average temperatures and a lower frequency of icing throughout the year, although frequencies are still moderate. The most significant potential for icing occurs within the altitude range of 3,000 to 15,000 ft, with higher frequencies during the December to March period. In the winter period, the icing frequencies around New York City are approximately 35%, with higher frequencies to the northwest of the city. Similar to Chicago, New York also undergoes seasonal shifts in icing altitudes and the frequency at which icing occurs. Altitudes where icing is prevalent rise in the spring and peak in the summer. In this period, icing frequencies from ground to 15,000 ft decrease to 5–15%. As fall and early winter bring cooler temperatures and more storms, icing frequencies increase again, and altitudes where icing occurs shift closer to the surface. Generally, icing frequencies are prevalent primarily in the hours surrounding sunrise.

For the San Francisco metropolitan area, the highest potential for icing also occurs from December through March, predominantly above 3,000 ft. Though San Francisco's cool, damp weather often brings low clouds and fog, near surface icing is rare due to temperatures typically being several degrees above freezing. For San Francisco, during the colder months, the icing frequencies tend toward 20%. In the shoulder months of November, April, and May, icing frequencies peak in the altitude band from 11,000 to 15,000 ft. Icing frequencies decrease in the springtime and are rare during the summer, even at higher altitudes. Results also indicate a relatively even distribution of icing throughout the day.

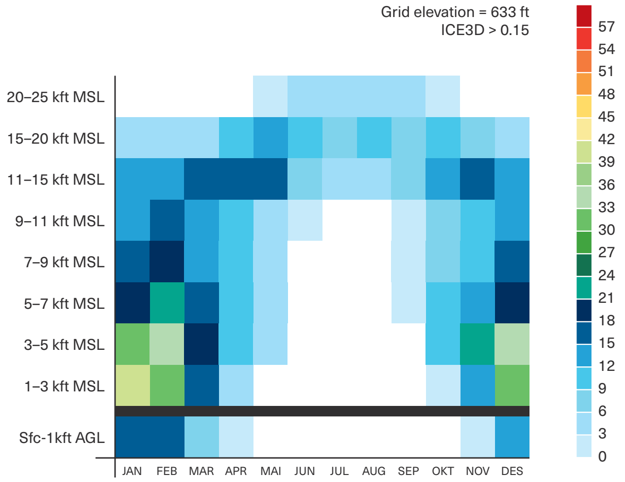
Los Angeles is, on average, the warmest of the four metropolitan areas and is naturally also the one least impacted by icing. Given the generally warmer temperatures at ground level year-round, icing frequencies remain relatively low near the surface. Instead, icing frequencies peak at higher altitudes, between 7,000 and 20,000 ft in the cold season and between 15,000 and 25,000 ft in the summer. During the cold season, the icing frequencies range between 5–15%. As a function of the time of day, icing frequencies resemble those of San Francisco, with a flat distribution throughout the day, although there is a noticeable peak in the morning to midday during July.

Finally, this report provides an overview of the current FAA regulations related to icing for AAM and possible ways to mitigate icing. The regulations are relevant for both small and large AAM aircraft. According to regulations, any aircraft must show the design characteristics to either operate in adverse conditions without loss of flight or loss of control, develop operating limitations that prohibit flight into these conditions, or show the ability to detect and safely exit inadvertent encounters with these conditions. Mitigative technologies will consist of a combination of meteorological forecasting products and onboard aircraft detection and protection systems.

A highlight of the report findings is shown in *Fig. 02*, where time-height frequency charts are provided for central locations for each of the four metropolitan areas. When combined with the FAA regulations, these charts allow an understanding of the influence of icing on an aircraft that is not protected and does not have ice detection capabilities on its cold-weather-based flight cancellation rate. The segment of the AAM sector, which targets operations at an altitude below 5kft, is looking at a flight cancellation rate of up to around 40% during the winter months in Chicago. For New York, this number is around 15–20%. San Francisco will experience less icing in these conditions in that altitude band and can expect the flight cancellation rate to be less than 10%. Lastly, for Los Angeles at the lower altitude bands under 5kft, the cancellation rate of operations will be quite rare.

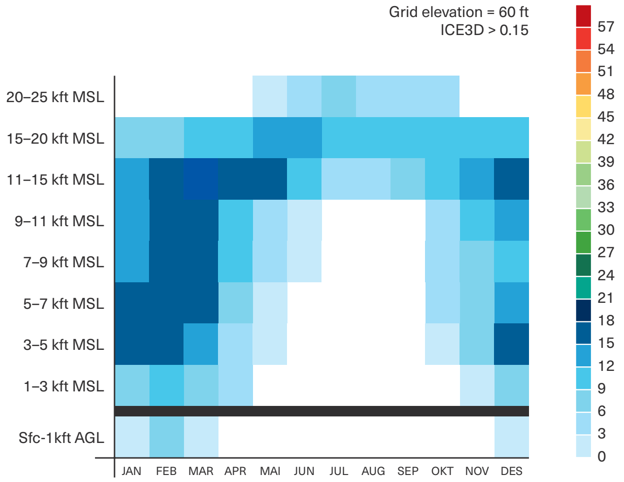
Chicago

Time-height frequency chart of downtown Chicago.



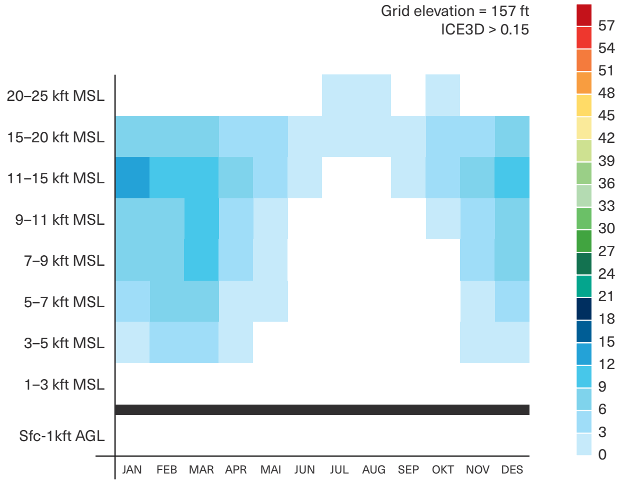
New York

Time-height frequency chart of Lower Manhattan, New York City.



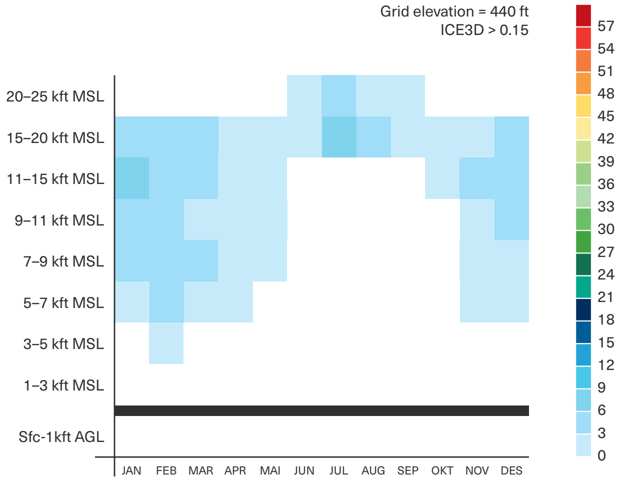
San Francisco

Time-height frequency map of Downtown San Francisco.



Los Angeles

Time-height frequency map of downtown Los Angeles.



2 Introduction

Present-day ground infrastructure and, in extension, logistics are challenged by increasing urbanization, which will see more than 60% of the world's population living in urban areas by 2030[1]. Urbanization combined with the overall growth of the world's population could add 2.5 billion people to urban areas by 2050[2].

Expanding the infrastructure network vertically instead of horizontally is a solution to infrastructure challenges – now and in the future – presented by the urban air mobility (*UAM*), regional air mobility (*RAM*), and the uncrewed aerial vehicle (*UAV*) community. Collectively, these growth industries are commonly referred to as the advanced aerial mobility (*AAM*) community. Drone package and cargo delivery companies, alongside air taxi companies, are spearheading innovation in this area.

Before providing beneficial solutions to society in general, companies in the AAM space must confront a long list of diverse and intrinsic challenges. Among them are public perception, technological obstacles, an uncharted certification landscape, and business viability. However, adverse weather conditions are perpetual challenges for the AAM industry's growth and maturity. The cause is related to the criticality of flight time for AAM business, where business models are based on assumptions about utilization rates and how adverse weather can result in AAM flight cancellations as it typically does for general aviation.

> *Once aircraft are operational, flight safety is critical. Out of all the things that influence flight safety, the weather is the most uncertain and influential.*

Thunderstorms, rain, lightning, and atmospheric icing (*or in-flight icing*) are some of the most dangerous weather conditions for aircraft [1,2]. This is especially true for AAM aircraft that operate in environments at altitudes that are heavily affected by the weather.

Icing can be extremely hazardous to civil and commercial aircraft [4,5,6]. Misconceptions that icing risks are confined to flights performed at mid-range altitudes, during winter, or only in the Arctic or subarctic regions are common. Multiple scientific studies have presented findings that have revealed icing as a global phenomenon [3]. Although they occasionally occur at higher altitudes, icing conditions are commonly found between the surface and 20,000 ft. Many commercial aircraft fly through and out of this atmospheric layer to cruise at altitudes above most icing situations. In contrast, AAM aircraft will tend to operate below 20,000 ft, where icing conditions are much more common.

For the purpose of this report, AAM aircraft are generally identified by their vertical take-off and landing (*VTOL*) capabilities, where most are equipped with lifting surfaces (*wings*) for support during horizontal flight. Typically, these aircraft are electrically powered, though some favor a hybrid propulsion system approach.

2.1 Objectives

While icing conditions occur across the entire United States, this report focuses on the frequency of icing impacts on AAM aircraft in a few select, large metropolitan areas promising for AAM operations - Los Angeles, San Francisco, Chicago, and New York. The objective of the report is to provide a substantiated reference document that enhances the AAM industry's understanding of icing, its many facets, potential commercial impact, and the need for concrete safety requirements related to airworthiness and certification.

2.2 Atmospheric icing

The term "atmospheric icing" relates to meteorological conditions where supercooled liquid water exists in the atmosphere. "Supercooled" refers to a state where the temperature of the water is below the freezing point while the water remains in a liquid state. Supercooled liquid water occurs mainly 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, water droplets can collide with the aircraft and freeze on its surface. This phenomenon is called in-flight icing, and it is a hazard that occurs globally and year-round on all types of aircraft [4,5]. Much research and development have been done to reduce the risk of icing to passenger-carrying aircraft, but it persists as a major threat to aviation safety [6].

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[1] World Cities Report 2020, The Value of Sustainable Urbanization.

[2] UN, Department of Social and Economic Affairs, 68% of the world's population is projected to live in urban areas by 2050.

Icing related to freezing precipitation is less frequent than in-cloud icing; however, it can be considerably more severe because water drops in precipitation are much larger than those in clouds. Icing from large water drops, including freezing rain and freezing drizzle, is called supercooled large droplet (*SLD*) icing. SLD can result in severe ice accretions, covering large surface areas, including those without ice protection, sometimes resulting in catastrophic consequences [7].

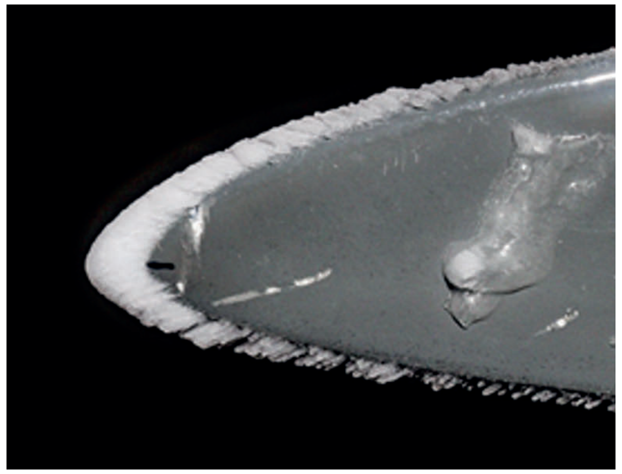
In-cloud icing and freezing precipitation are not the only icing hazards to aircraft. Frost occurs when a cold surface encounters warm and moist air. In this case, the water vapor forms a thin layer of ice on the cold surface. Such "ground icing" refers to the accumulation of ice on an aircraft before 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.

There are three different types of ice formed during in-flight icing encounters; rime, glaze, and mixed ice (*see pictures on the right*). The main driver for the different ice types is temperature, but also airspeed, liquid water content, and droplet size can influence the resulting ice type.

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

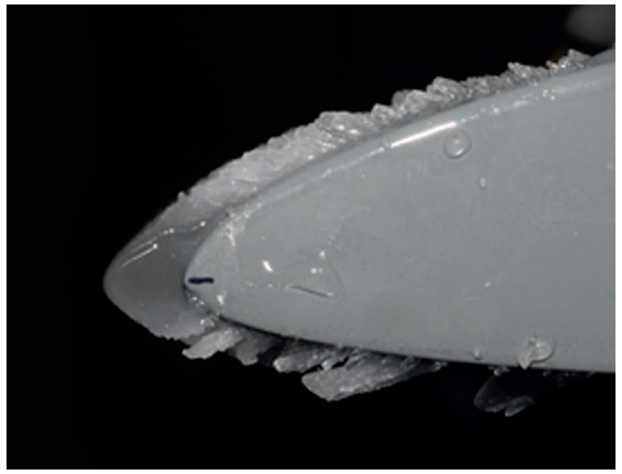
Glaze ice is also known as clear ice, and it tends to form at temperatures near the freezing point (*typically temperatures above -3°C*). In this temperature regime, the incoming droplets typically do not freeze instantly but remain in their liquid phase for a longer period. The resulting liquid water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

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



Rime ice

Glaze ice



Mixed ice

2.3 Icing effects on AAM aircraft

When an AAM aircraft encounters icing conditions, three critical elements will be affected, 1) rotors and propellers, 2) flight-critical sensors (*primarily the airspeed sensor*), and 3) aerodynamic surfaces (*including wings, empennages, and engine/cooling inlets*).

Rotors can accumulate large amounts of ice very quickly. The rotors generate lift and propulsion, keeping the aircraft airborne and maneuvering. Several studies have shown that rotor blades can lose up to 80% lift and experience an increased torque by more than 200% within 2 minutes of entering icing conditions [8]. Ice also increases the drag on the blades and limits the maximum rotation rate of the motor or engine. Furthermore, the high centrifugal forces acting on ice that has built on the rotor blades can lead to the shedding of ice fragments. In turn, ice shedding can lead to imbalances in the rotor dynamics and high vibrations that can damage the motor or engine. Rotor and propeller icing is, therefore, one of the primary hazards for AAM aircraft, as the loss of performance can rapidly converge towards unsustainable flight and potential loss of the aircraft.

Inadvertently flying into icing conditions also leaves an unheated airspeed sensor exposed. Because of the airspeed sensor's small size, shape, and design (*generally, it is a tube with a hole at the tip*), it is one of the first aircraft elements to accumulate ice. If the hole at the tip is blocked or clogged, the sensor measurements will be inaccurate, which is a severe hazard that has led to numerous aircraft crashes for both uncrewed and passenger-carrying aircraft [6].

Most AAM aircraft optimize efficiency using wings to generate lift during horizontal flight. However, ice accretion on aerodynamic surfaces, e.g., wings, alters the geometric shape of the wing profile, significantly decreasing aerodynamic performance, generating less lift, more drag, and stall at lower angles of attack compared to normal operational conditions.

A study on UAV wings found that severe icing conditions were accountable for reducing aerodynamic lift by 35%, reducing the stall angle by 33%, and increasing aerodynamic drag by more than 400% [9].

2.4 Special icing challenges for AAM aircraft

AAM aircraft face several particular technical challenges related to icing, different or amplified from those of a conventional passenger-carrying aircraft.

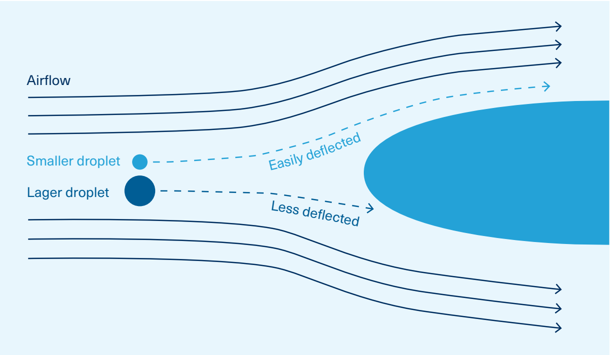
2.4.1 Vehicle type

Icing effects and severity depend on the type of AAM aircraft design. Designs that heavily rely on rotary wings to generate lift will be more sensitive to icing than designs that use fixed wings to generate lift during horizontal flight. Large rotors are generally less susceptible to icing compared to small rotors [10], implying that designs that rely on multiple small rotors are especially sensitive to icing.

2.4.2 Size

Small rotors and wings accumulate ice faster compared to larger ones because larger airfoils displace more air than smaller ones [11]. The result is greater deflection forces on droplets. While droplets of all sizes can impinge on an airfoil, larger droplets are less deflected and thus impinge with a higher efficiency on the airfoil (*see Fig. 01*). This effect is known as the collection efficiency. Thus, small wings and rotors tend to accumulate more ice per unit area than larger ones. Because AAM aircraft are typically smaller than conventional passenger-carrying aircraft, they are substantially more sensitive to icing compared to airliners. Since AAM rotors are mostly smaller than helicopter rotors, they are also similarly more sensitive to icing.

Fig. 01



2.4.3 Flight velocity

High airspeeds lead to aerodynamic heating on wings, which can counteract icing to some degree, especially at temperatures close to the freezing point. However, as AAM aircraft operate at lower airspeeds than typical passenger-carrying 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 [11].

2.4.4 Laminar airflow

The Reynolds number (*a dimensionless number describing flow patterns*) is approximately an order of magnitude lower for AAM aircraft than for passenger-carrying aircraft. Consequently, AAM aircraft operate in flow regimes where laminar flow effects are more prevalent than turbulent flow at high Reynolds numbers. In addition, because the laminar flow is more easily disturbed, the ice and surface roughness lead to higher penalties than that under turbulent flow.

2.4.5 Weight

Aside from the aerodynamic penalties induced by icing, AAM aircraft are typically very weight-sensitive, and any imbalances or unaccounted-for weight increases could have significant consequences. Therefore, the added mass from ice accretions can quickly become critical as the additional weight can impact the aircraft's center of gravity, stability, and maneuverability. Ice mass can cause substantial vibrations when ice shedding leads to imbalanced ice mass distributions on rotors.

2.4.6 Sensors

The most critical sensor concerning icing is the airspeed sensor. Ice can block the pitot tube and/or the static port, leading to erroneous airspeed indications. The indicated airspeeds can become locked at the airspeed value indicated when the icing failure occurs, drop to zero airspeed, or gradually change. This failure mode depends on the location of the ice blockage within the instrument. Autopilots are typically incapable of detecting erroneous airspeed readings and may initiate maneuvers that can potentially crash the vehicle (*stall or nose dive*). Furthermore, a means of ice detection is necessary for AAM aircraft to support the pilot in identifying hazardous icing conditions with low liquid water contents (*which can be difficult to detect visually*). Antennas can also be affected by icing, which limits their functionality and adds ice weight.

2.4.7 Autopilots and controls

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

2.4.8 Cruise altitude

Commercial large passenger transport aircraft (*airliners*) typically have a cruise altitude of 30,000–35,000 ft, i.e., above the altitude where icing conditions most often exist. Further, ascending and descending are typically only a relatively small part of the entire flight for such aircraft. The risk of flying into potential icing conditions is a function of the potential icing frequency for a given area and the time spent in the altitude band where icing occurs. Generally, all AAM aircraft will spend 100% of all operations in this altitude band. In addition, flights are typically not conducted for aircraft without any detection or protective measures if any clouds are present and the temperatures are below freezing or close to freezing due to the risk of icing. At airports, sensors are used to accurately determine cloud ceiling height, but away from these sensor locations, ceiling heights can be difficult to determine, and the mere risk of entering into potential icing conditions due to local variations in ceiling height would potentially cause planned flights to be canceled.

3 Climate Analysis Chicago, NY, SF, LA

Given the risk of icing and the associated limitations on operations, it is valuable to consider the climatological frequency of icing conditions around major metropolitan areas where AAM flights are likely to increase dramatically in the coming years.

This report introduces this topic by providing a general overview of the frequency of atmospheric icing conditions within the metropolitan areas of Chicago, New York, San Francisco, and Los Angeles and their surroundings.

3.1 Scope

This study is based on meteorological observations and forecasts collected over the last decade. 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 four metropolitan areas. The findings of this study are translated in terms of the potential consequences for the AAM service providers and those relying on their services.

3.2 Background

Data from ERA5 (*fifth generation ECMWF re-analysis*) meteorological grids have been used in this study [12]. 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 ECMWF (*European Center for Medium-range Weather Forecasts*) was combined with observations from satellites, radars, surface stations, weather balloons, etc., to provide high-quality global analyses. Each of these datasets has proven to be highly useful in assessing 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 cloud layering. For ERA5, the result is a high-quality combination of essential icing-relevant meteorological data that provide a solid foundation for assessing the frequency of the existence of meteorological conditions conducive to icing [3].

For this study, ERA5 grids of icing-relevant fields were examined every 3 hours (*00, 03, 06, 09, 12, 15, 18, and 21 UTC*) at 31-km/0.25° grid spacing, covering the years from 2010 to 2019 (*the most recent complete decade of data*). Three-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 at ground level.

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

3.3 Icing assessment methodology

Before presenting the results of the study, an explanation of how they are developed and what they represent is first required. Meteorologists who study and guide aircraft into icing conditions for research and aircraft certification developed an algorithm (*ICE3D*) to assess the likelihood of icing at every 3D data point in the grid every three hours throughout this ten-year period. The likelihood value ranges from 0.0 (*icing is not expected*) to 1.0 (*icing is highly likely*) and is determined based on the atmospheric parameters indicative of icing conditions described above, including cloud coverage, temperature, moisture, 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 AAM operations would most likely be canceled, that is when clouds 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. A frequency value of 0% indicates that the potential for icing on an AAM aircraft is essentially zero. In comparison, values approaching 100% indicate that conditions conducive to icing are extremely likely to be present, which could inhibit safe AAM operation without ice protection.

Three different representations have been chosen to present the findings of the study and to convey the underlying significance of icing as a problem for AAM industries. The three representations are time-height frequency charts across the year, diurnal frequency charts for each month, and full-column monthly frequency maps. A brief introduction to each type of representation follows.

3.3.1 Time-height frequency charts

Time-height frequency charts indicate the frequency of potential icing conditions across the year over the operational airspace at locations of interest across each of the metropolitan areas. The results are divided into altitude bands. Time-height frequency maps provide insight into how icing tends to be distributed vertically and how icing altitudes tend to change over the course of the year.

These charts show the fraction of time when the ICE3D algorithm indicated that the potential for icing exceeded a threshold within an altitude band for each month. 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 is of particular importance for AAM aircraft operations. The remaining series of altitudes are altitude bands relative to mean sea level (*MSL*), where different subsets of AAM aircraft are operated.

3.3.2 Diurnal frequency charts

The diurnal frequency charts provide information about the icing distribution with altitude over the course of the day for a single location during each month. This provides an understanding of the specific time intervals during the day and night at which flight operations are more or less likely to be impeded by potential icing conditions.

In these charts, the horizontal axis represents the time of day, with each mark corresponding to a three-hour interval. This is similar to the time-height plots, with the vertical axis representing the different altitude bands. The charts thereby indicate the fraction of time where icing conditions are expected for a given time of day at each altitude for each month.

3.3.3 Full-column monthly frequency maps

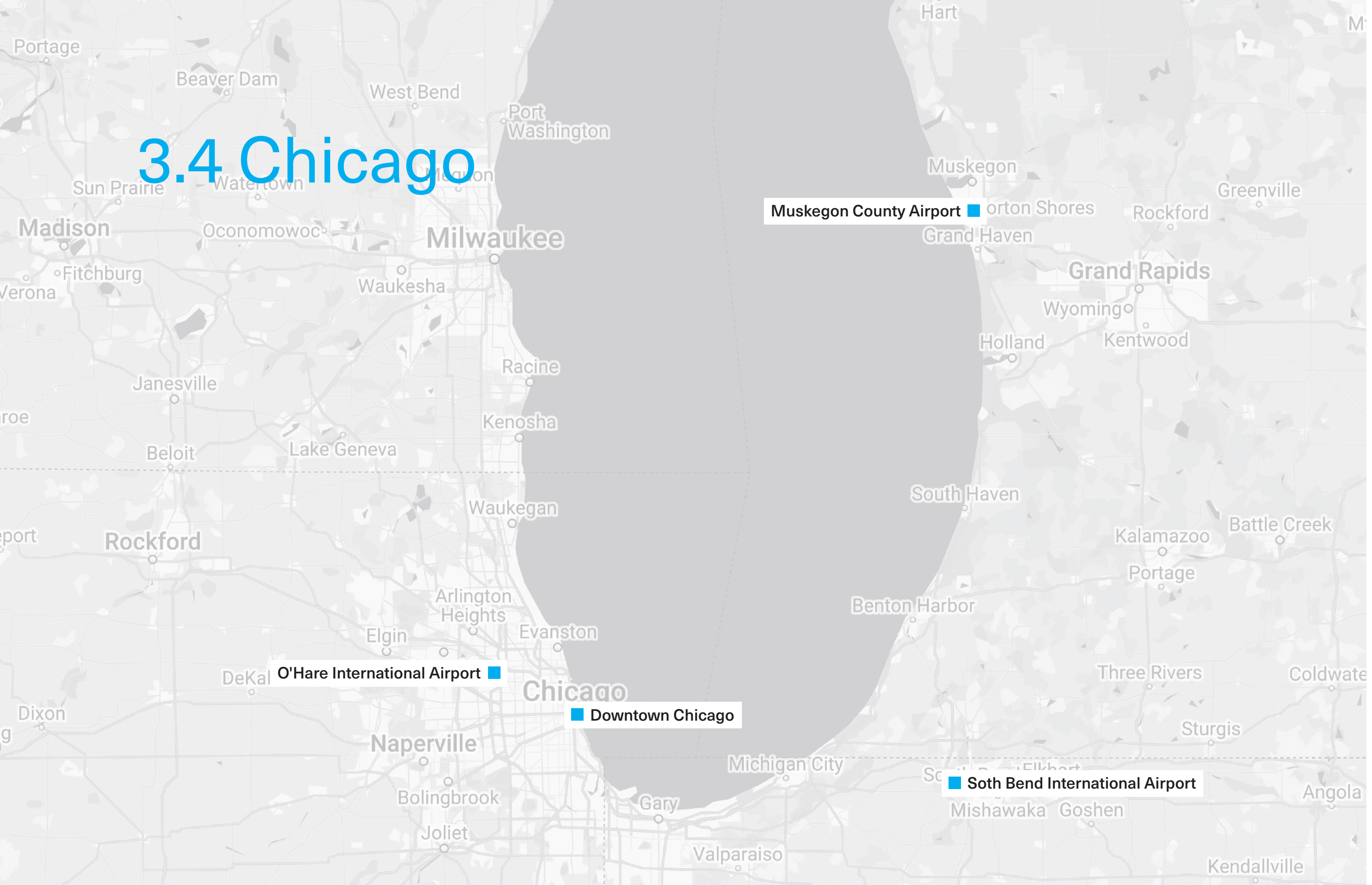
The full-column frequency maps (*Figure x–y*) represent the fraction of time for each month where the mapped areas had ICE3D values that exceeded the selected threshold. The chart shows the icing frequencies for the complete operational airspace from the ground level to 15,000 ft – the chosen altitude ceiling for the full-column monthly frequency maps. If the ICE3D threshold was met in any of the altitude bands, the entire height column is identified as having icing for the corresponding 3-hour data point grid.

A 15,000 ft ceiling is higher than the altitudes most AAM aircraft will be operating in. However, the reasons for this ceiling are twofold: First, one objective of the report is to target as wide an audience as possible, covering many different applications. The operational envelopes of AAM aircraft will vary widely. For a regional commuter aircraft, the operational ceiling will be higher than for a small package delivery aircraft.

Secondly, cloud ceilings can be difficult to determine, and the mere risk of potential icing conditions would potentially cancel operations. While airports are equipped with sensors that measure cloud ceiling and icing conditions accurately, estimation between sample points can be more difficult.

The color chart in *Figures X to Y* signifies the percentage of time that conditions conducive to icing are present for each of the twelve months. An area filled with white would have a 0% likelihood of possible icing conditions in that specific month. Conversely, an area filled with shades of green would have a 35–70% likelihood of potential icing conditions during that month. Areas filled with yellow, orange, or red shades have the potential for icing somewhere in the vertical column more than 70% of the time during that month.

3.4 Chicago



A map of the greater Chicago area with the four different areas for which time-height frequency has been investigated.

The City of Chicago is the most populous city in the state of Illinois and the third-largest city in the United States, following New York and Los Angeles. The Chicago metropolitan area's climate is categorized as continental. The four seasons are distinctly represented by freezing temperatures during the winter months and hot and humid summers. Chicago is located along the shore of Lake Michigan, one of the Great Lakes of North America. The states of Indiana and Michigan are to the east of Chicago.

3.4.1 Time-height frequency – Chicago

The time-height potential icing frequency from downtown Chicago (*Fig. 02*), Chicago O'hare International Airport (*ORD, Fig. 03*), Muskegon County Airport in Michigan (*MKG, Fig. 04*), and South Bend International Airport in Indiana (*SBN, Fig. 05*) are provided at right. These plots demonstrate the seasonal changes in potential icing altitudes for the Chicago Area, with potential icing frequencies being largest close to ground level during the colder months and at higher altitudes during the summer months.

Comparing downtown Chicago to other sites outside the Chicago area, the differences are noteworthy. For example, further to the east at South Bend, Indiana, and Muskegon, Michigan, the downwind effects of Lake Michigan are quite apparent. Here, greater frequencies of icing potential are present below ~5.000 ft during the cold season. At higher altitudes, the icing frequencies are very similar to those over Chicago because high-altitude icing is dominated by synoptic-scale storm systems passing through the region rather than by the lake, which primarily affects icing at low altitudes.

3.4.2 Diurnal – Chicago

The diurnal patterns and their seasonal shifts are presented in *Fig. 06* as a set of monthly time-height icing frequency charts. The diurnal patterns are indicative of the impact that icing will likely have on AAM aircraft operating in the Chicago metropolitan area at different times of the day.

Near-surface icing frequencies peak during the coldest months of the year, December through February, and, to a lesser extent, March. During these months, icing frequencies tend to peak from 09 to 15 UTC (*corresponding to 3 am to 9 am, local time in Chicago*) in the hours surrounding sunrise. Near-surface icing frequencies decrease somewhat in the afternoon to just after sunset, from 1 pm to 7 pm (*CDT*), but remain above 25%. These diurnal patterns are attributed to the fact that near-surface temperatures are the coolest, and cloud bases tend to be lowest in the hours before dawn and in the morning. The reverse is true in the afternoon, where surface temperatures typically reach their diurnal maximum and ceiling heights tend to be somewhat higher.

Throughout the rest of the year, near-surface icing frequencies are less frequent, with the summer months experiencing icing only at higher altitudes.

3.4.3 Full-column monthly frequency – Chicago

Monthly maps of potential icing frequency for the region surrounding Chicago and covering altitudes from the surface to 15,000 ft are presented in *Fig. 7*.

> *During the relatively cold months of November to February, the potential icing frequencies in the area are moderate-to-high, with frequencies above 50% due to the frequent presence of cool, moist air from storms passing through the region.*

These frequencies are enhanced over and downwind of Lake Michigan by lake-effect clouds generated as cold, northwesterly winds pass over the relatively warm open waters of the lake, causing icing clouds to form over the lake and advect over areas immediately downwind of Lake Michigan [13]. In these areas, peak icing frequencies are enhanced, reaching values on the order of 60–75%. During the warm season (*roughly April to September*), lake-effect cloud production is generally not a factor, and consequently, icing is much less frequent below 15,000 ft.

Fig. 02

Time-height frequency chart of downtown Chicago.

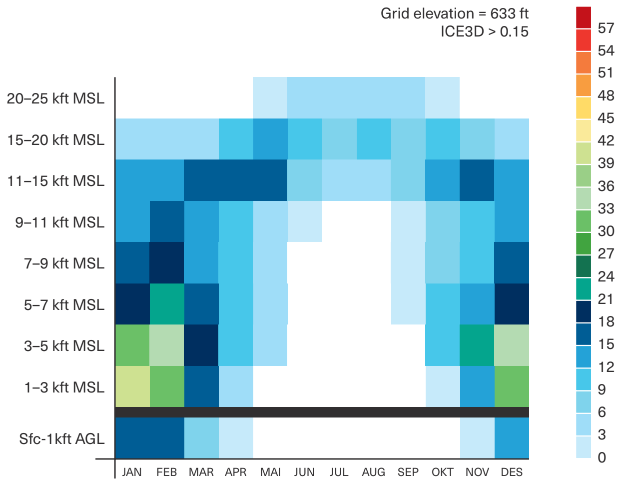


Fig. 03

Time-height frequency chart of Chicago O'Hare International Airport (*ORD*).

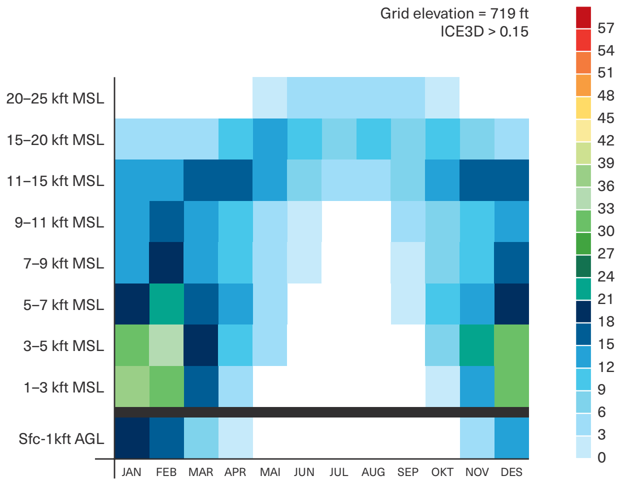


Fig. 04

Time-height frequency chart for Muskegon County Airport (*MKG*).

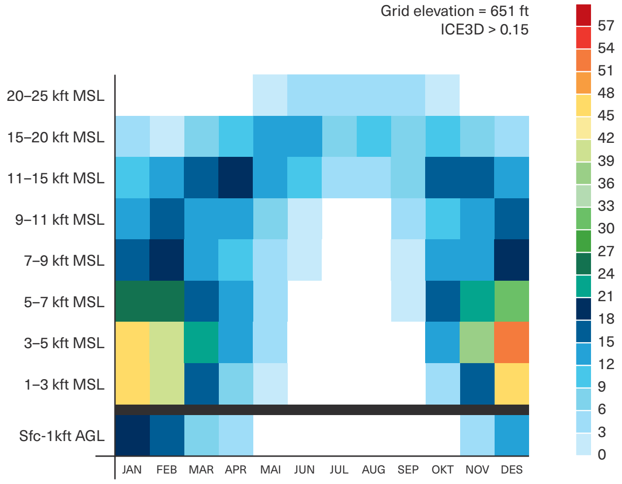
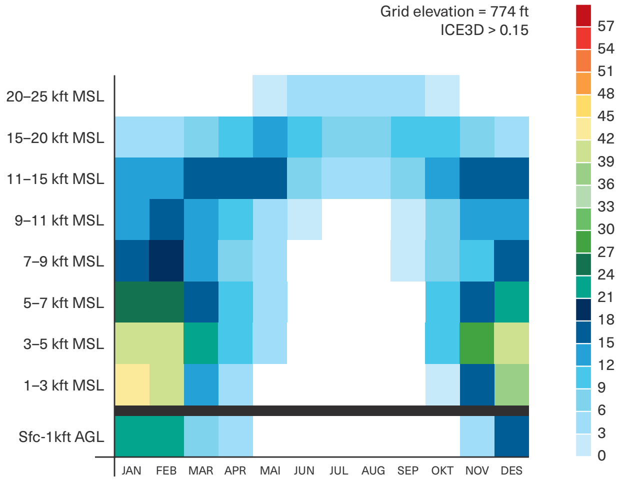


Fig. 05

Time-height frequency chart for South Bend International Airport (*SBN*).



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[1] *A meteorological length scale in the order of 620 miles or more.*

Fig. 06
Diurnal, time-height charts of icing frequencies for downtown Chicago in zulu time. Note that the color scale used is compressed to 0–60%.

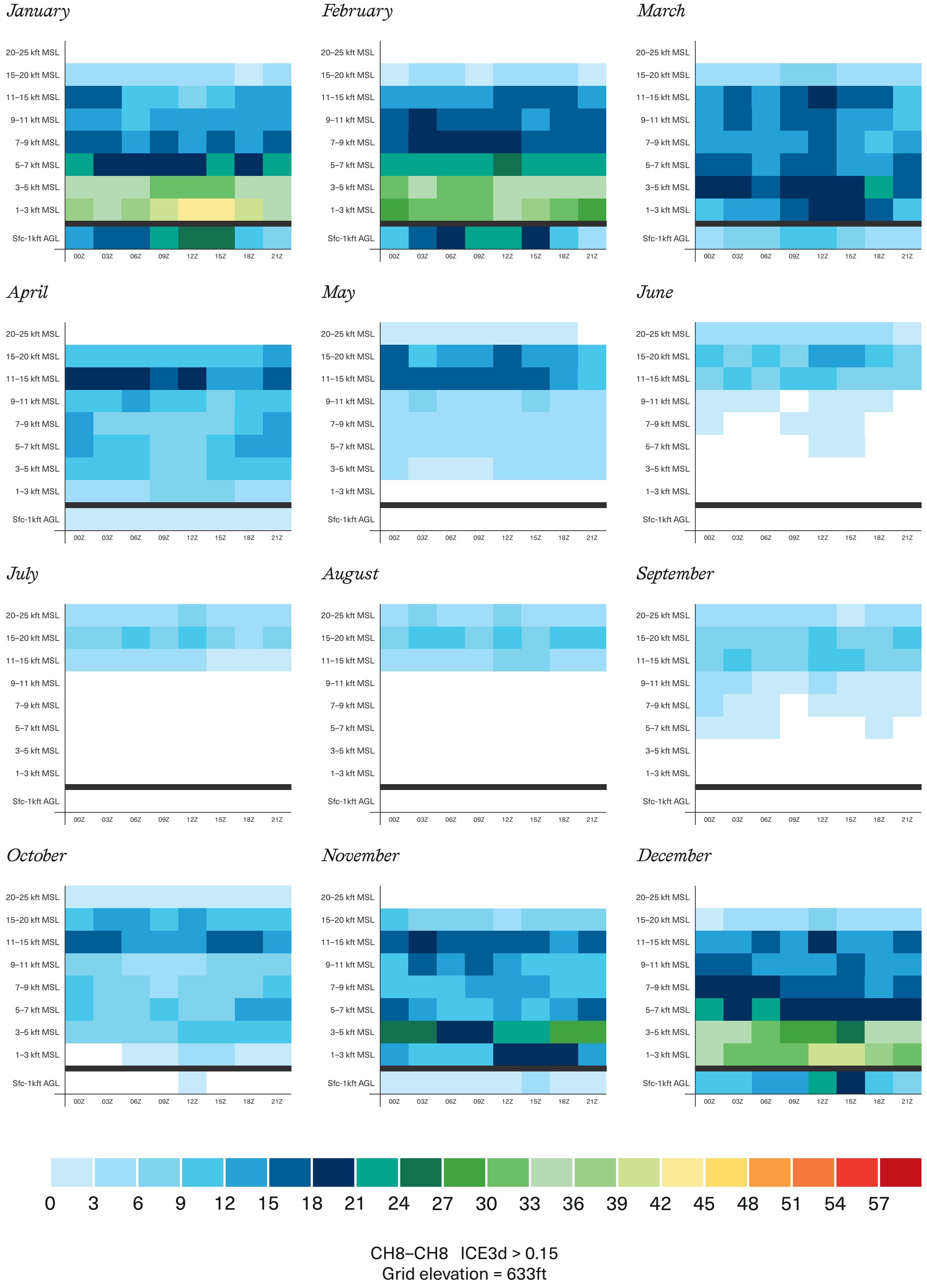
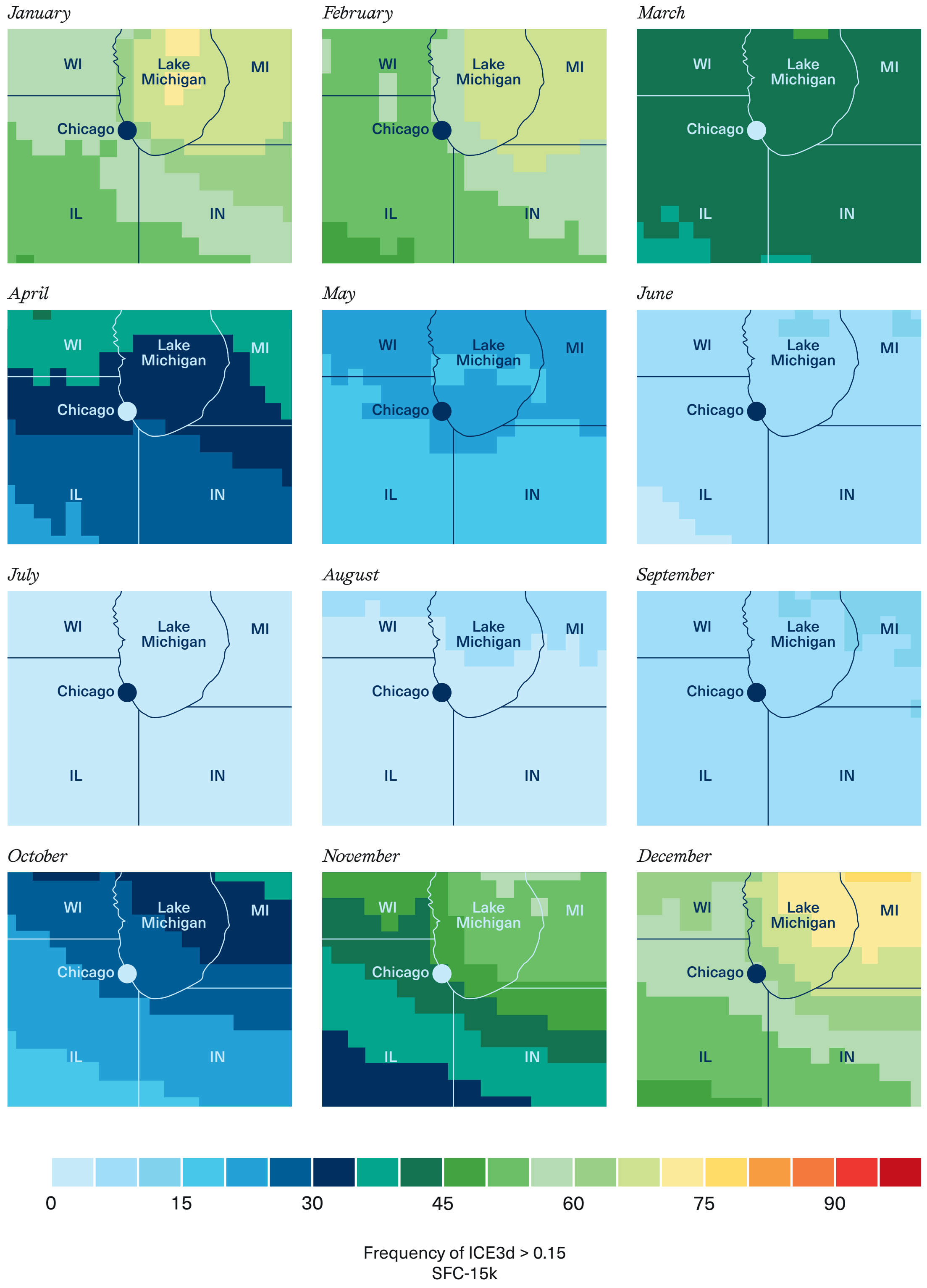


Fig. 07
Maps of the icing frequencies for the greater Chicago area surrounding Lake Michigan over the different months of the year.



3.5 New York

A map of the greater New York City area with the four different areas for which time-height frequency has been investigated.

The New York metropolitan area is located along the East Coast and includes New York City, the most populous city in the United States. The New York City metropolitan area is located in the transitional zone between humid subtropical and humid continental climates and experiences hot and humid summers as well as chilly and damp winters. The New York metropolitan area is located on the coast of the Atlantic Ocean, and the terrain rises toward the Northwest.

3.5.1 Time-height frequency – NY

Time-height potential icing frequency plots for New York City and surrounding locations at Newark Liberty International Airport (*EWR*), John F. Kennedy International Airport (*JFK*), and northwest of the city (*NY1*) all have highly similar patterns in seasonal icing altitude and frequency as seen in *Fig. 08–11*. This behavior is also exhibited in the other areas of the New York metro area, with somewhat higher frequencies toward the northwest. Low-altitude icing around New York City is most prevalent between December and March, but peak frequencies are generally less than 20%. Potential icing frequencies tend to be highest between 3,000 and 15,000 ft, especially between December and March. This effect is attributed to the storm systems that are highly dynamic around New York when conditions are relatively moist and cool. Icing altitude bands rise from spring into summer when icing is no longer a threat at low altitudes. This pattern is reversed during the fall, where icing altitudes shift downwards again, and near-surface icing becomes a reality again starting in December.

3.5.2 Diurnal – NY

Similar to Chicago, there is evidence of diurnal patterns and seasonal shifts in icing frequency around New York, as shown in *Fig. 12*. Some of these patterns are more subtle. Near-surface icing frequencies generally peak between between 09 and 15 UTC (*corresponding to 10 pm to 10 am local time, New York*), essentially the middle of the night to mid-morning, with the same reasons noted for Chicago. This peak is maximized in February. There is also a cold-season afternoon maximum in icing frequencies at 3,000–7,000 ft. This is associated with maximized atmospheric instability during this part of the day. Instability happens when temperatures decrease relatively rapidly with altitude, which is at least partially driven by the sun heating the ground. The instability causes air near-surface air to rise, where it can sometimes saturate and form icing clouds.

3.5.3 Full-column monthly frequency – NY

Fig. 13 presents the monthly maps of potential icing frequency for the region surrounding New York.

> *During the coldest parts of the year, December through March, maximum potential icing frequencies exceeding 35% were present around New York City, with higher values present to the northwest of the city.*

The increase in frequencies toward the northwest is likely due to the increase in elevation, as well as the greater influence of storms passing through the eastern Great Lakes. Between November and February, there is a corridor of lower icing frequencies over New York City, with maxima to the northwest and southeast. The decrease from the northwest of the city to the city itself is associated with a downslope effect when the northwesterly flow is present, while the increase to the southeast of the city is associated with icing clouds that form over the Atlantic Ocean when those cold northwest winds interact with the relatively warm waters offshore. In addition, storm systems commonly pass by to the southeast of New York City, keeping many of the icing clouds just offshore. This combination results in relatively high icing frequency over the Atlantic Ocean to the southeast of New York.

As noted earlier, seasonal shifts in icing frequency are also present in New York. Icing altitudes shift upward during the spring to reach their maximum altitudes during the summer when frequencies are only 5–15%. As fall and early winter usher in cooler temperatures and more storms, icing frequencies increase, and icing altitudes shift closer to the surface.

Fig. 08

Time-height frequency chart of Lower Manhattan, New York City.

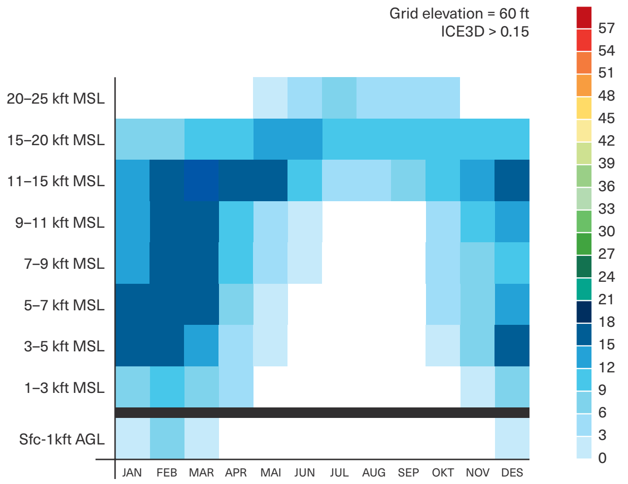


Fig. 09

Time-height frequency chart of Newark International Airport (*EWR*).

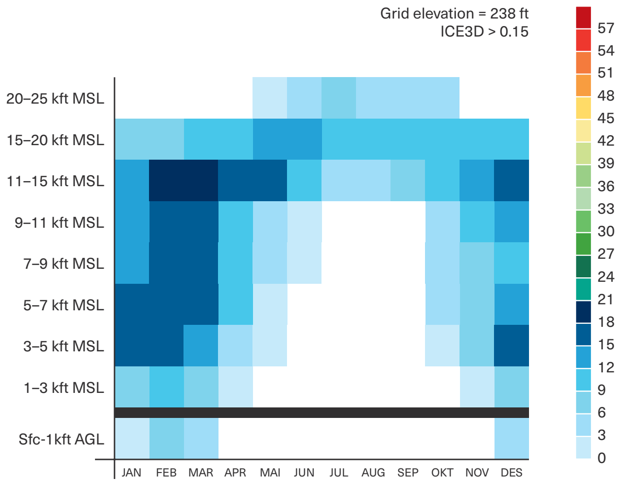


Fig. 10

Time-height frequency chart for John F. Kennedy International Airport (*JFK*).

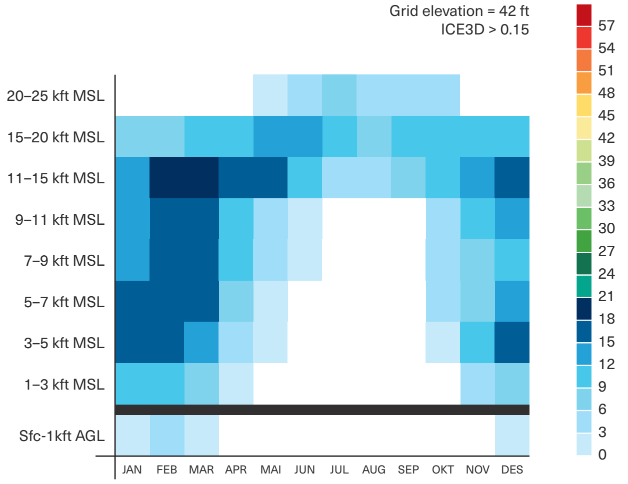


Fig. 11

Time-height frequency chart for a location to the northwest of New York City.

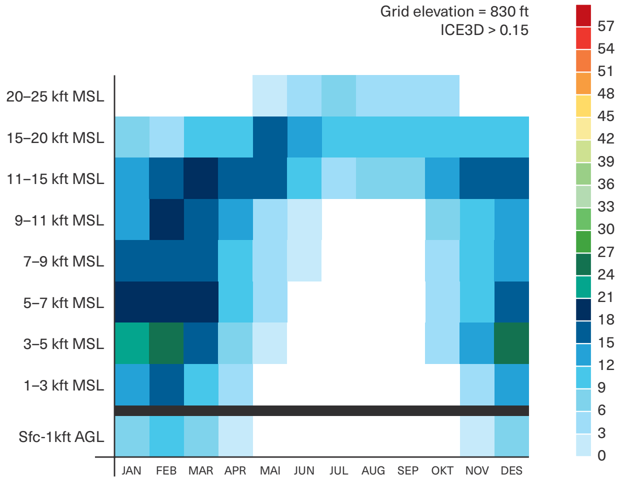
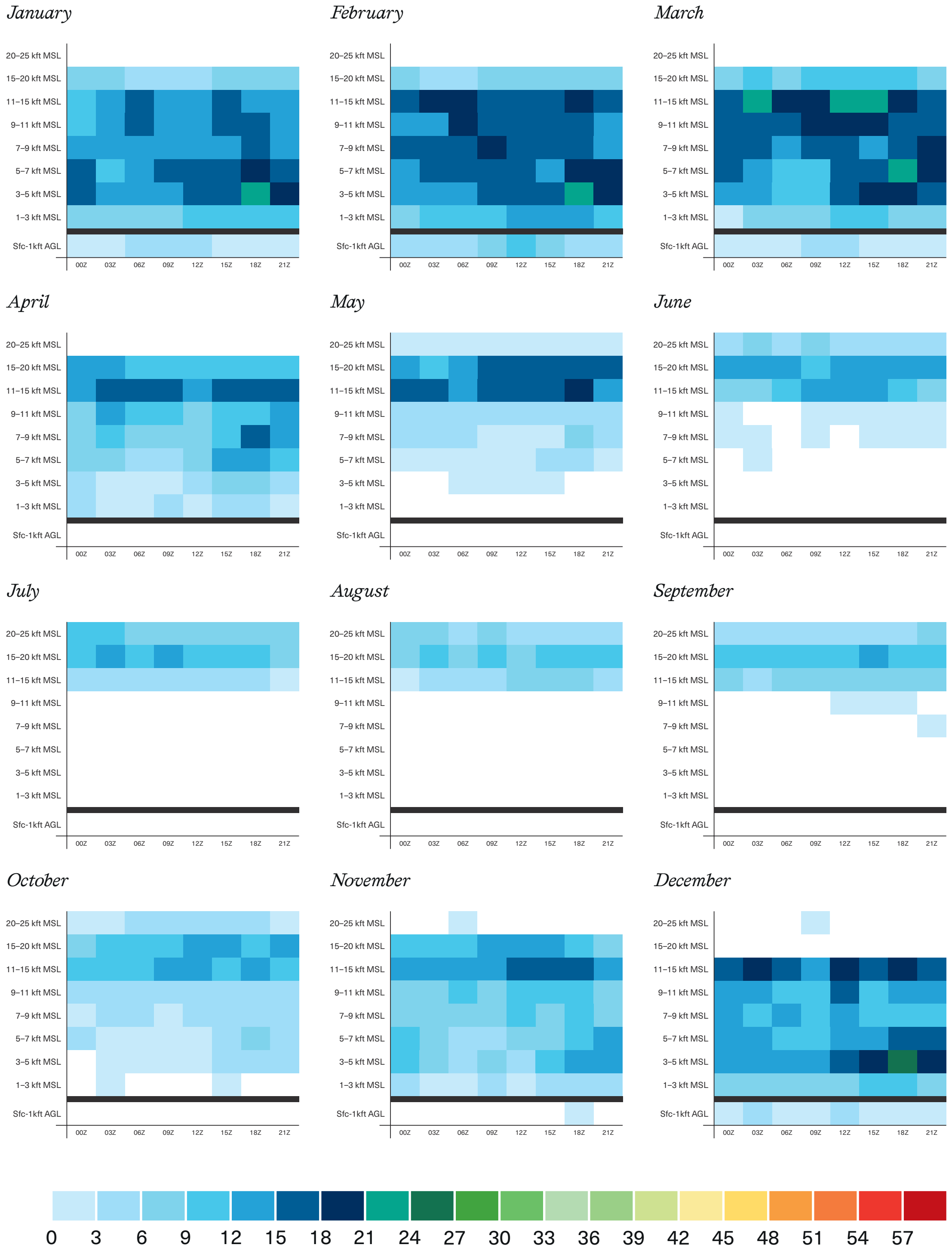


Fig. 12

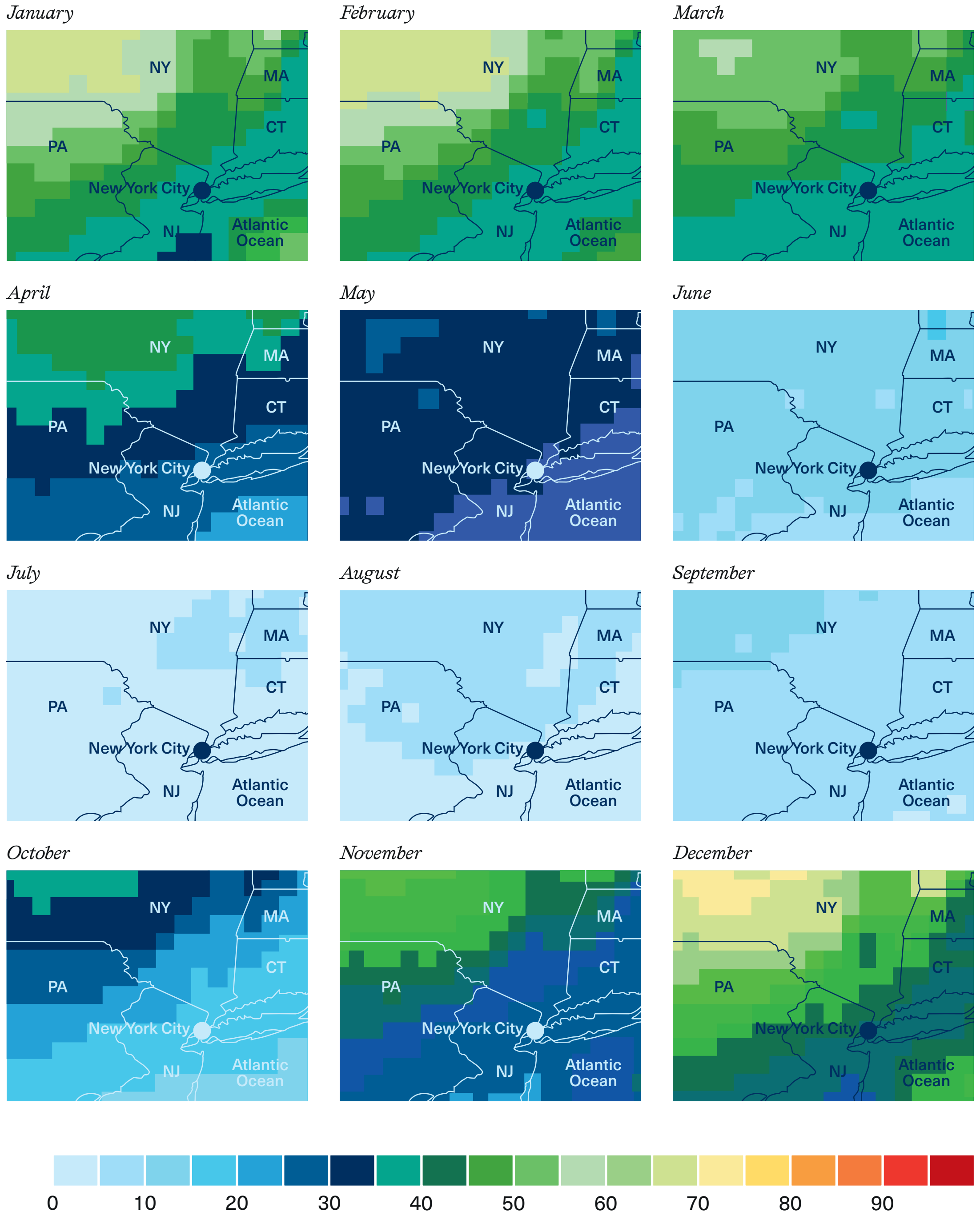
Diurnal, time-height charts of icing frequencies for Lower Manhattan, New York City in zulu time. Note that the color scale used is compressed to 0–60%.



NYC – New York City/Lower Manhattan
ICE3d > 0.15 Grid elevation = 60ft

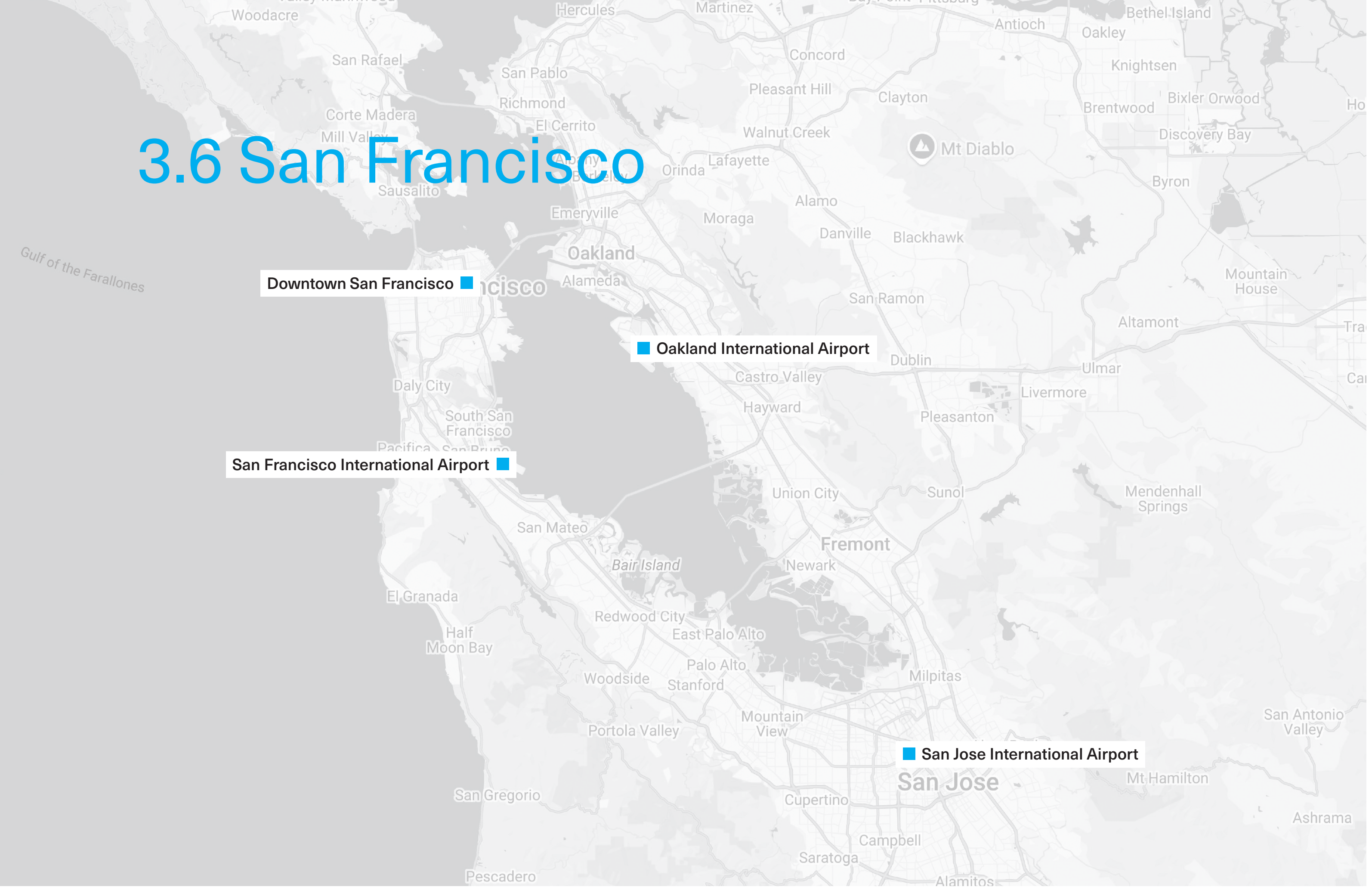
Fig. 13

Maps of the icing frequencies for the greater Metropolitan area surrounding New York over the different months of the year.



Frequency of ICE3d > 0.15
SFC-15k

3.6 San Francisco



A map of the greater San Francisco area with the four different areas for which time-height frequency has been investigated.

The San Francisco metropolitan area is located along the West Coast of the United States and encompasses numerous cities, such as Oakland, San Jose, and, of course, San Francisco itself. The topography of the area is rather complex.

3.6.1 Time-height frequency – SF

The time-height potential icing frequency plots for San Francisco and surrounding areas are shown in *Fig. 14–17*, representing Downtown San Francisco (*SF5*), Oakland International Airport (*OAK*), San Francisco International Airport (*SFO*), and San Jose International Airport (*SJC*). Not surprisingly, these locations exhibit nearly identical behavior with respect to the vertically distributed icing frequencies and patterns. The potential for icing conditions is highest during the months from December to March when storm systems tend to be most active in the area. Icing is most commonly found at altitudes above 5,000 ft MSL. The "shoulder season" months of November, April, and May also have some icing potential, which is relatively evenly distributed between 3,000 and 20,000 ft, maximizing in the 11,000–15,000 ft altitude band. Icing is less frequent between June and September. Near-surface icing is rare in the San Francisco area despite its reputation as having cool, damp weather. While this weather often results in low clouds and fog that can prove troublesome for AAM operations, near-surface temperatures are generally several degrees above freezing, limiting icing altitudes to several thousand feet above the ground.

3.6.2 Diurnal – SF

The diurnal monthly frequency charts for downtown San Francisco (*S5; Fig. 18*) indicate that the icing frequencies are relatively evenly distributed over the day. While there can be strong diurnal trends in the frequency of near-surface fog and low clouds, the weather at higher, cooler altitudes where icing exists tends to be driven by larger-scale storm systems that can cause icing to develop at any time of day.

Across the region, icing frequencies have fairly similar patterns in the months of January to March. The exception is the elevated hills located to the northeast of San Francisco, where icing shows up in the lowest altitude band in the hours near dawn during December and February (*not shown*). This difference is likely driven by the cooler near-surface temperatures in this area of higher elevation, plus terrain-enhanced lift (*"upslope"*) that can result in a greater frequency of near-surface icing clouds.

Icing frequencies in the San Francisco region decrease during the spring months and are rather uncommon during the summer, even at altitudes above 11,000 ft.

3.6.3 Full-column monthly frequency – SF

Fig. 19 presents the monthly maps of potential icing conditions over the San Francisco region.

> *Frequencies are in the order of 20% around the San Francisco metropolitan area during the cold season.*

Higher values are evident along the elevated terrain of the Sierra Mountains located to the northeast, near the border between California and Nevada, where they surpass 50% in December. That area is known for icing and significant snow in the winter as moisture from the Pacific Ocean is carried inland and lifted along the western slope of the terrain. The frequency of potential icing conditions is relatively uniform across the San Francisco metropolitan area, with a gradual increase from south to north evident between November and April. This tendency generally matches the higher frequency of storms toward the north. Also, the area around Mendocino National Forest to the northwest has a local icing maximum, particularly evident in March, when frequencies reach ~35–40%. Icing frequencies gradually decrease in the spring across the San Francisco area. They are quite low in the summer and gradually increase again in the fall as conditions cool and storm systems return.

Fig. 14
Time-height frequency map of Downtown San Francisco.

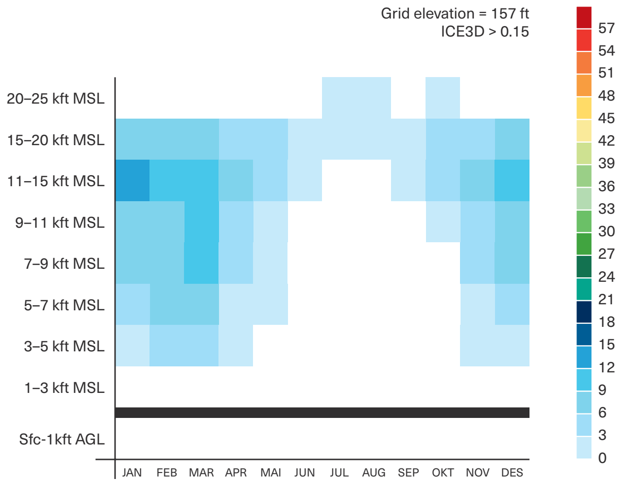


Fig. 15
Time-height frequency map of Oakland International Airport (*OAK*).

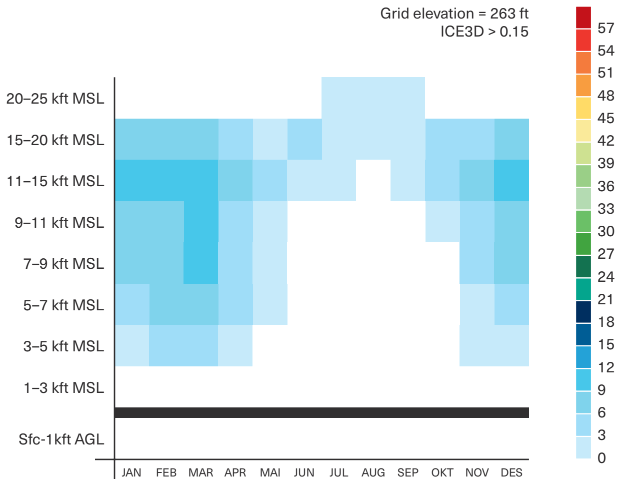


Fig. 16
Time-height frequency map for San Francisco International Airport (*SFO*).

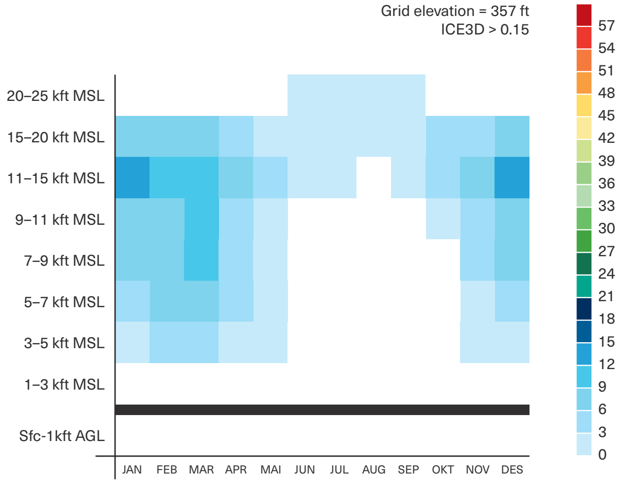


Fig. 17
Time-height frequency map for San Jose International Airport (*SJC*).

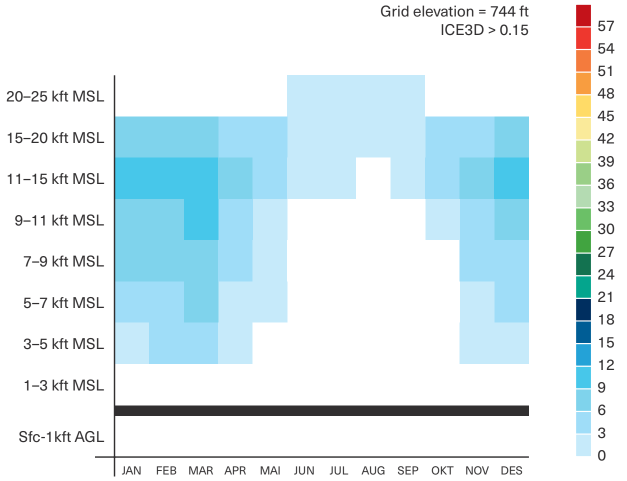


Fig. 18

Diurnal, time-height charts of icing frequencies for Downtown San Francisco in zulu time. Note that the color scale used is compressed to 0–60%.

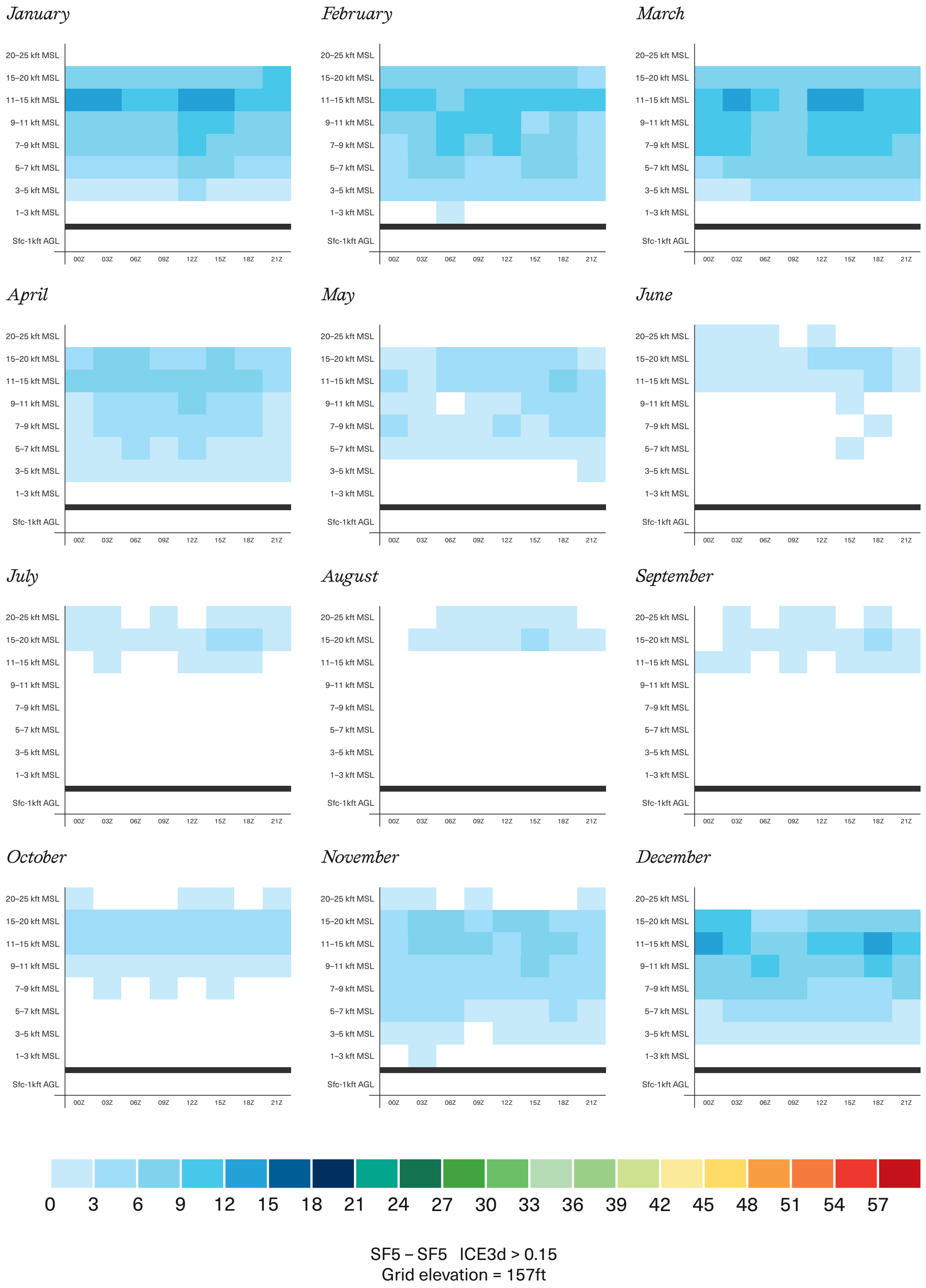
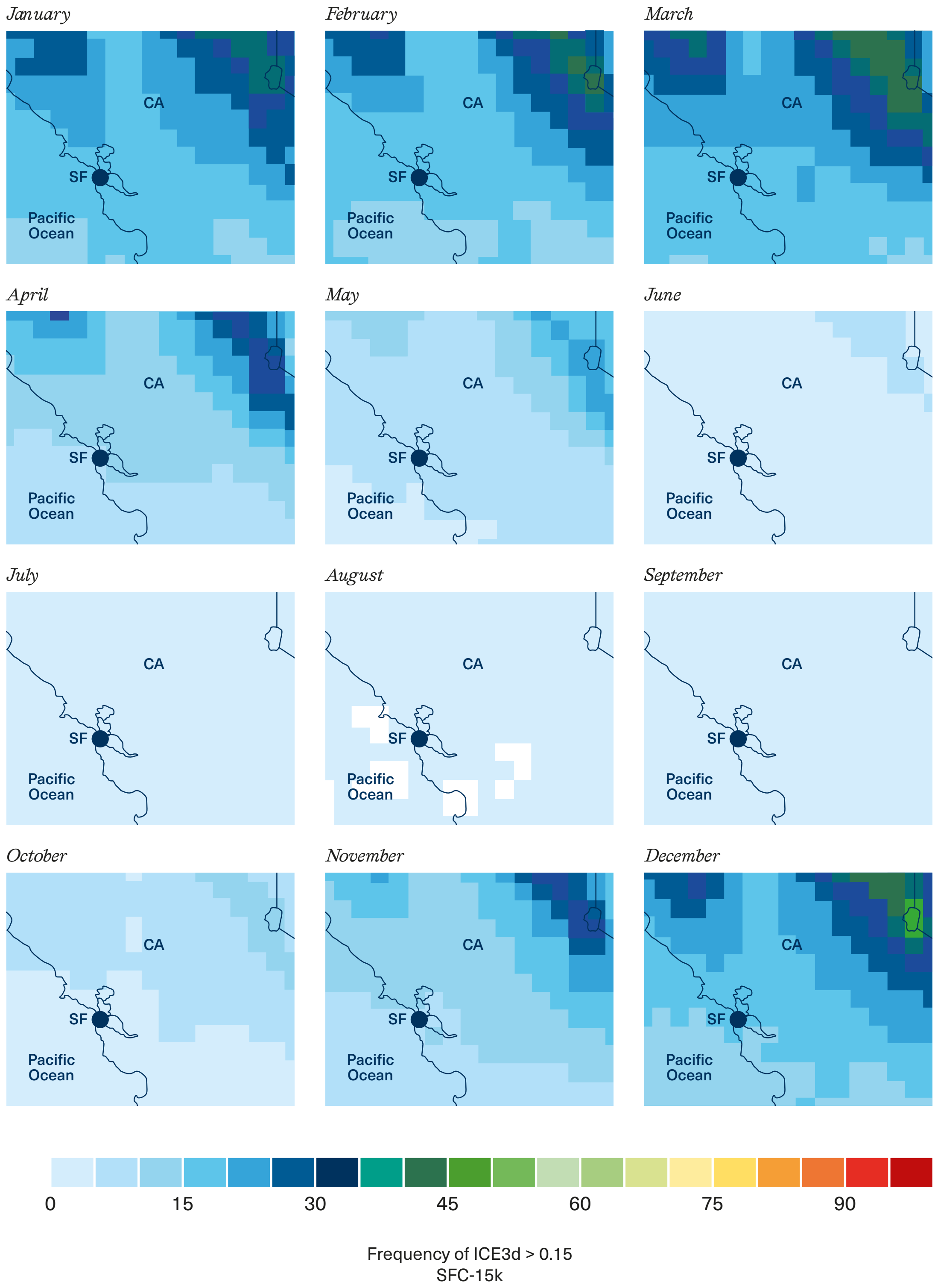
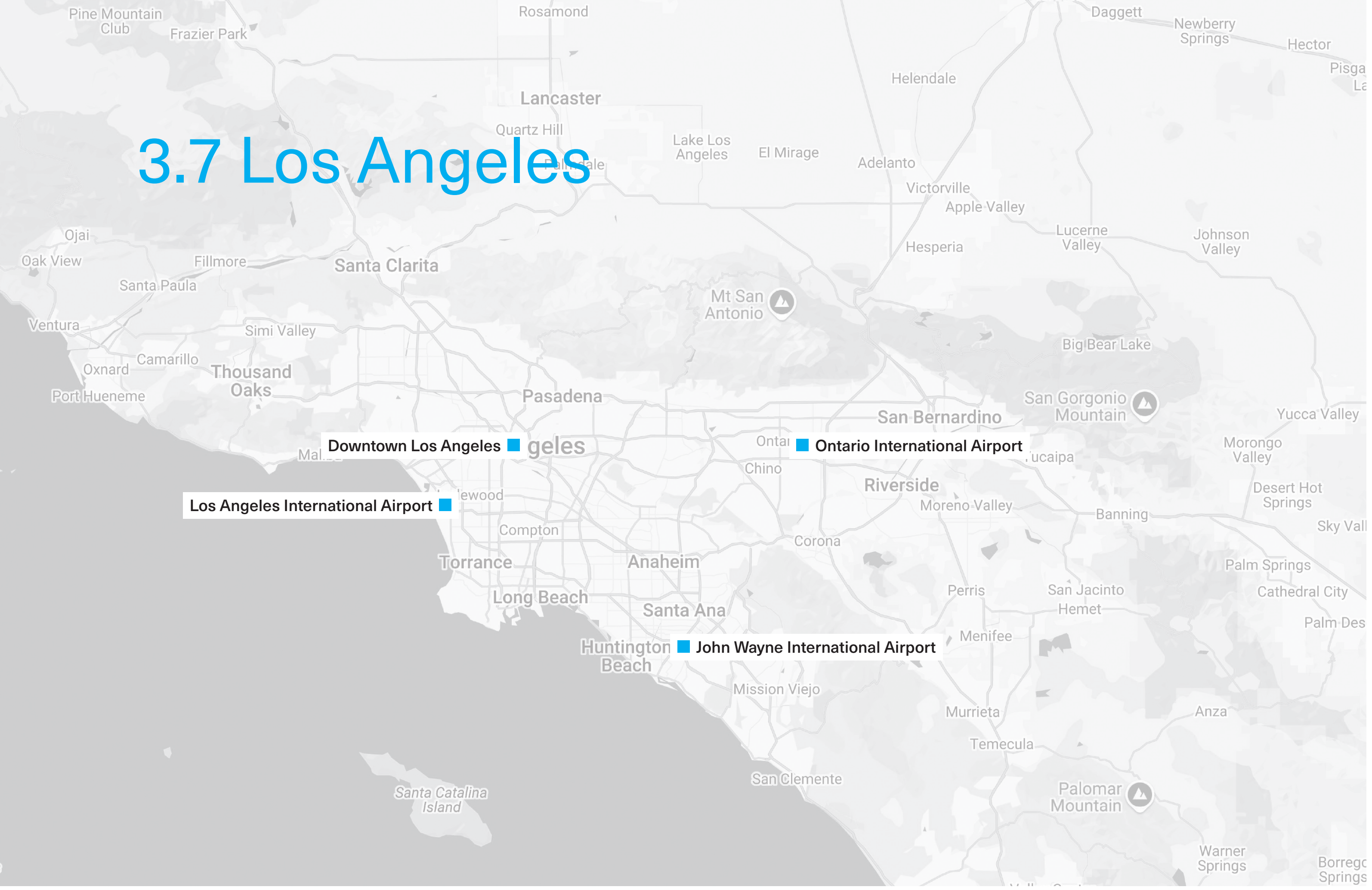


Fig. 19

Maps of the icing frequencies for the greater Metropolitan area of San Francisco over the different months of the year.



3.7 Los Angeles



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Los Angeles is the most populous city in California and the second most populous city in the United States. Wedged between the Pacific Ocean and the San Gabriel Mountains, the underlying Los Angeles Basin containing most of the city is a coastal lowland area. Out of the four metropolitan areas covered in this report, the greater Los Angeles area is the warmest and driest. Despite having relatively little precipitation, Los Angeles is affected by fog, which can prove troublesome for AAM operations. It is most frequent in the autumn and winter but can occur year-round.

3.7.1 Time-height frequency – LA

Similar to San Francisco, time-height icing potential frequency plots for sites across the Los Angeles area are remarkably similar (*Fig. 20–23*). Once again, this is due to icing events being primarily associated with large-scale storm systems passing through and affecting the entire area. Given the relatively warm ground-level temperatures present throughout the year, icing frequencies are quite low near the surface and are instead maximized at higher altitudes, between 7,000 and 20,000 ft during the cold season and between 15,000 and 25,000 ft during the summer. The locations for the time-height frequency maps are Downtown Los Angeles (*LA2*), Los Angeles International Airport (*LAX*), Ontario International Airport (*ONT*), and Orange County (*SNA*). There are only minor discernable differences between the four locations.

3.7.2 Diurnal – LA

The diurnal patterns and their season shifts over the greater Los Angeles area are relatively comparable to the San Francisco area, although frequencies are slightly lower (*Fig. 24*).

The exception to these flat diurnal frequency patterns is during July when frequencies seem to peak in the morning to early afternoon, local time Los Angeles (*corresponding to 15 to 21 UTC*).

Icing is almost non-existent at near-surface altitudes but still does occasionally occur, especially in the elevated hills to the east-northeast of Los Angeles. There, it primarily occurs during the night or morning hours , between November and March (*not shown*).

In general, the icing frequency around Los Angeles is the lowest out of the four metropolitan areas investigated in this report.

3.7.3 Full-column monthly frequency – LA

A collection of monthly height-frequency maps of the Los Angeles region is presented in *Fig. 25*.

> *Potential icing frequencies are relatively low throughout the year. That said, they are maximized during the cold season at 5-15%.*

During these months, there is a tendency for icing to be found across the broader coastal area, where occasional storms bring moisture from the Pacific Ocean inland. Icing frequencies are quite low from June to October.

Fig. 20
Time-height frequency map of downtown Los Angeles.

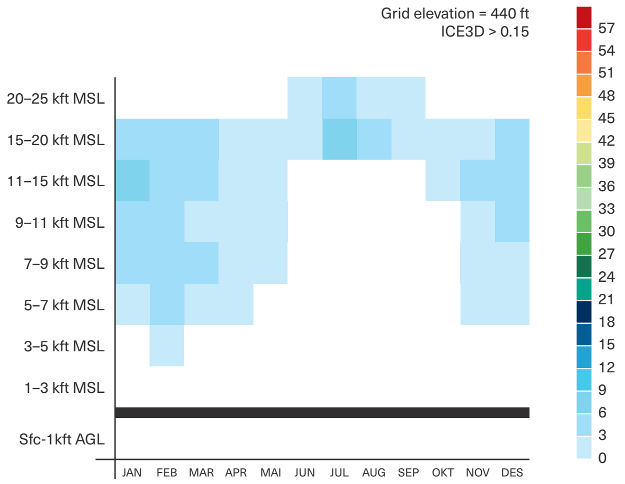


Fig. 21
Time-height frequency map of Los Angeles International airport (*LAX*).

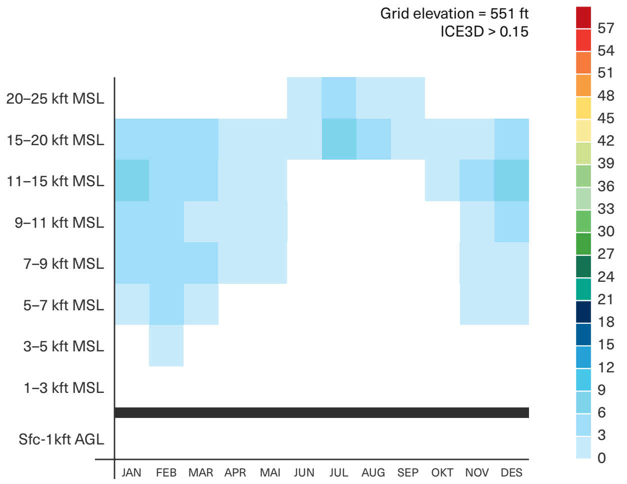


Fig. 22
Time-height frequency map of Ontario International Airport (*ONT*).

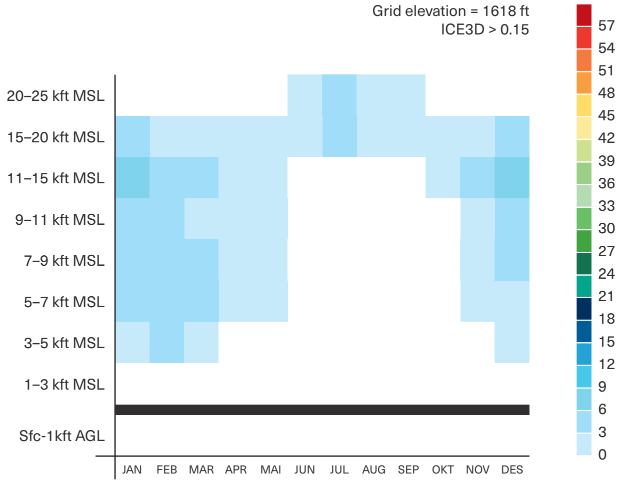
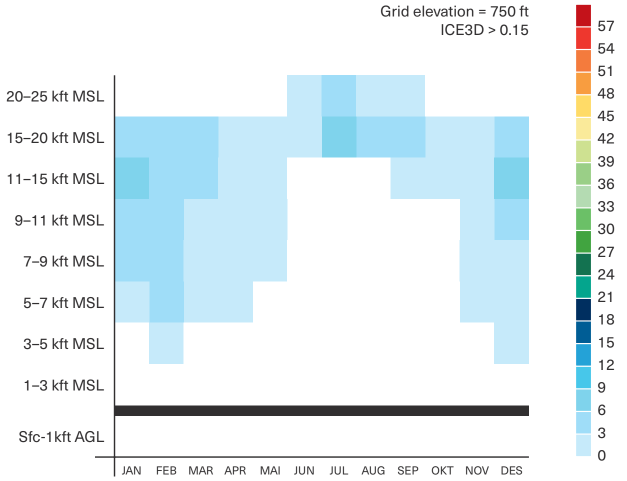


Fig. 23
Time-height frequency map of Orange County.



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[5] *Plot not included in the report for the sake of brevity, but can be provided by authors upon request*

Fig. 24
Diurnal, time-height charts of icing frequencies for Downtown Los Angeles in zulu time. Note that the color scale used is compressed to 0–60%.

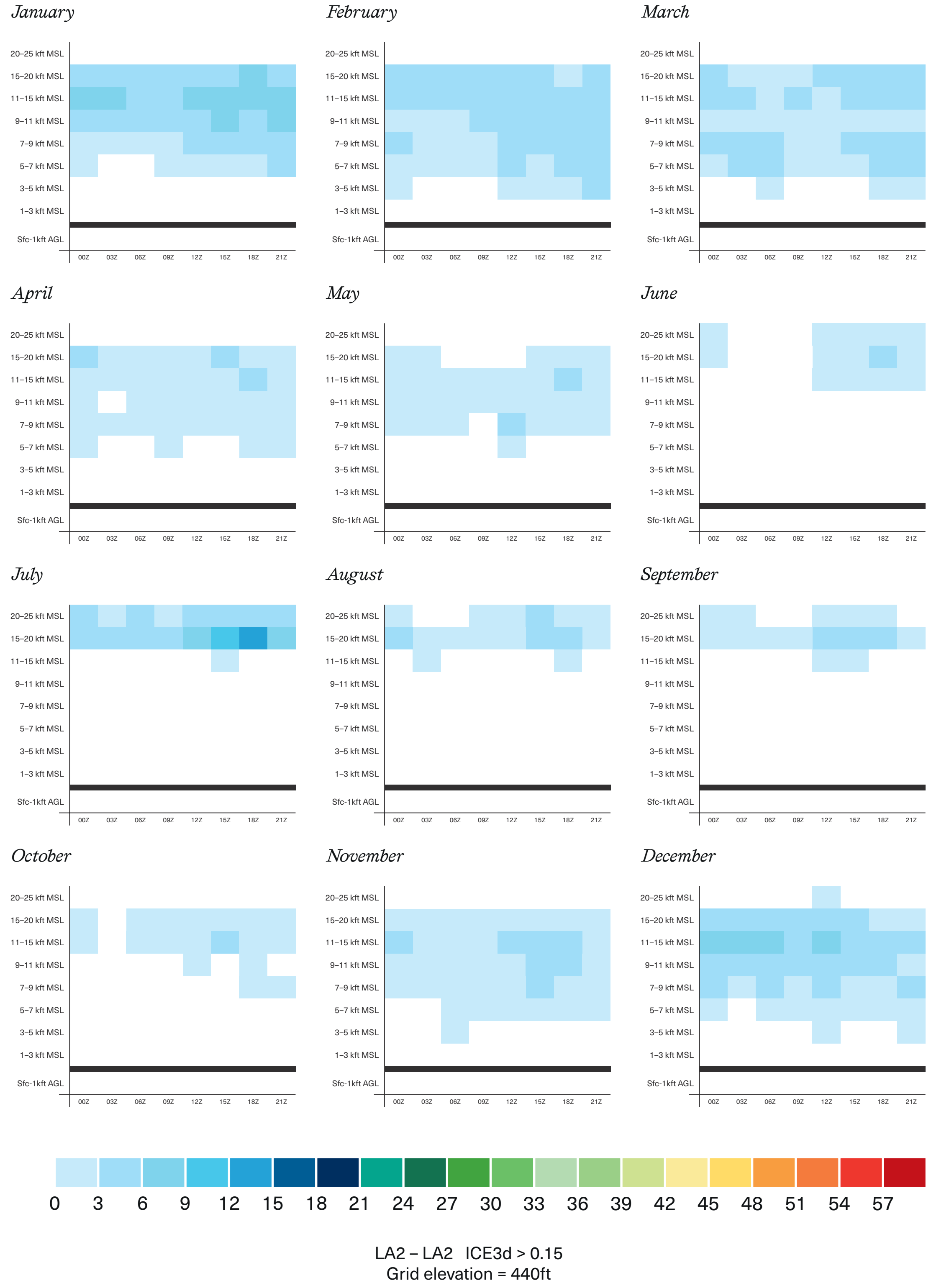

Fig. 25
Maps of the icing frequencies for the greater Los Angeles area over the different months of the year.

4 Icing consequences for the AAM industry

This section accounts for how The Federal Aviation Administration (FAA) regulates adverse weather conditions, including icing, for AAM aircraft. It includes the categorization of aircraft and proposed airworthiness criteria and means of compliance for the different aircraft types on the topic of icing.

4.1 FAA AAM Limitations

4.1.1 Small Unmanned Aircraft

Small, low risk unmanned aircraft (*UA*), typically less than 100 lb. (*45 kg*) maximum take-off weight, are being type certified in accordance with the FAA's Durability and Reliability process. Airworthiness regulations are published in the U.S. Federal Register for each applicant. The regulations for adverse weather are as follows:

"D&R.130 Adverse Weather Conditions

> (*a*) For purposes of this section, 'adverse weather conditions' means rain, snow, and icing.
>
> (*b*) Except as provided in paragraph (*c*) of this section, the UA must have design characteristics that will allow the UA to operate within the adverse weather conditions specified in the CONOPS without loss of flight or loss of control.
>
> (*c*) For adverse weather conditions for which the UA is not approved to operate, the applicant must develop operating limitations to prohibit flight into known adverse weather conditions and either:
>
> (*1*) Develop operating limitations to prevent inadvertent flight into adverse weather conditions; or
>
> (*2*) Provide a means to detect any adverse weather conditions for which the UA is not certificated to operate and show the UA's ability to avoid or exit those conditions."

To date, only one small UA applicant believes they may be able to operate in some icing conditions and detect icing conditions for which they must exit. None of the other applicants have proposed a design which incorporates ice detection or protection systems. Means of compliance to (*c*)(*1*) require the UFM (*Unmanned Aircraft Flight Manual*) Limitations section to prohibit flight in potential icing conditions – visible moisture (*clouds, precipitation, fog or mist*) at ambient temperatures below +5°C. This limitation is more conservative than a "known" icing limitation which many applicants have proposed.

The FAA has recently implemented a new process, called Criteria for Making 44807 Determinations (*CMD*), that permits small package delivery unmanned aircraft to operate commercially without a type certificate beyond visual line of sight. The airworthiness criteria and means of compliance are the same as in the Type Certificate process but CMD allows for self-certification with minimum FAA oversight. The CMD process will eventually be promulgated into a new regulation.

4.1.2 Large Unmanned Aircraft

The FAA has received type certificate applications for unmanned fixed-wing aircraft ranging in size from 3,500 lb. to 10,000 lb. maximum takeoff weight. They are expected to be certified in the continuous maximum and intermittent maximum cloud icing conditions but not SLD icing conditions. The certification standards imposed on them will be similar to part 23 airplane standards. The Airplane Flight Manual (*AFM*) Limitations section will prohibit flight in severe icing conditions and conditions that are determined to contain freezing rain or freezing drizzle and an immediate exit from these conditions if encountered.

4.1.3 Urban Air Mobility Aircraft

The proposed FAA certification basis for each of these aircraft are published in the Federal Register and will be based on part 23 (*normal category airplanes*), part 27 (*normal category rotorcraft*), part 33 (*aircraft engines*) and part 35 (*propellers*). Special conditions will be added to account for new and novel technologies such as the electric engine and vertical takeoff and landing (*VTOL*) capability. The majority of these aircraft will not incorporate ice protection systems for the airframe or propeller/rotor and will not be certified for icing. Several manufacturers have proposed limitations in potential icing conditions (*visible moisture and ambient temperature below +5°C*), in addition to prohibiting flight in known icing.

4.2 Mitigating icing for AAM aircraft

4.2.1 Small Unmanned Aircraft

Weather products are the proposed means of compliance to (*c*)(*2*) of D&R.130 (*see 6.1.1*). Compliance with the UFM Limitations will require ambient temperature for those that don't incorporate a temperature sensor (*and most do not*). The ability to avoid moisture will require knowing the cloud ceiling and the location of precipitation, fog, and mist. The challenges of providing the existence of these for the altitudes and areas where small UA will operate were discussed in section 2.4.8.

4.2.2 Large Unmanned Aircraft

The FAA has received type certificate applications for fixed-wing designs and these aircraft are expected to be certified to part 23 airworthiness standards. Most of these aircraft will be certified for icing, but not SLD. An ice detection system, a SLD detection system and the ability to safely exit an inadvertent SLD encounter will be required. Weather products to avoid SLD and its sub-categories are needed to reduce risk.

4.2.3 Urban Air Mobility Aircraft

Most designs will be prohibited from flight in icing conditions, and proposed standards will require the AFM Limitations section to prohibit flight in potential icing conditions (*as defined in section 6.1.1*), if the aircraft does not incorporate an ice detection system. Certification standards will address safe exit from inadvertent icing encounters. These standards, which are not required for conventional airplanes and rotorcraft not certified for icing, will include the effects of ice accretion on propeller/rotors and the airframe. These aircraft will be equipped with temperature sensors, but weather products are needed to help operators minimize inadvertent icing encounters.

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[6] *defined in ASTM F3478 as "a UAS operated in accordance with the concept of operations (CONOPs), eligibility criteria, and kinetic energy threshold specified in the G-1 Issue Paper (provided to the applicant by the FAA). Kinetic energy threshold of 25,000 lb is the maximum certified under D&R to date.*

[6] *https://www.faa.gov/uas/advanced_operations/certification/criteria_special_classes*

[7] *ASTM F3120/F3120M-20, "Standard Specification for Ice Protection for General Aviation Aircraft"*

[9] *https://www.federalregister.gov/documents/2024/03/08/2024-04690/airworthiness-criteria-special-class-airworthiness-criteria-for-the-joby-aero-inc-model-jas4-1*

5 Summary

The AAM industry promises groundbreaking changes in urban transportation and logistics, but challenges like atmospheric icing need addressing for the industry to reach its full potential. This report examines the impact of atmospheric icing on AAM aircraft and their operations, analyzing four major US metropolitan areas: Chicago, New York, San Francisco, and Los Angeles.

When an aircraft encounters icing conditions, ice starts accumulating on the aircraft, affecting the aerodynamics and onboard systems such as the airspeed sensor. Icing poses a severe risk and, if unmitigated, can lead to disastrous events. Furthermore, AAM aircraft face heightened risks due to their size and operational characteristics.

The study contained in this report reveals icing patterns and frequencies based on a decade of data using an icing estimation algorithm and the ERA5 dataset. Chicago experiences frequent icing, peaking at lower altitudes with frequencies over 50% from ground to 15,000 ft. New York is exposed to a slightly more moderate amount of icing, with total frequencies in the order of 35% around NYC in the colder months from December to March, centered primarily between 3,000 and 15,000 ft. San Francisco sees icing less than the New York area, primarily above 3,000 ft and around 20% during winter months. In the warmest of the four metropolitan areas, Los Angeles, icing is least frequent. Very rarely occurring at lower altitudes, even in the coldest months, constitutes less than 20% of the time between ground and 15,000 ft.

This report also briefly accounts for FAA regulations in the AAM space and potential mitigation measures.

5.1 Outlook

This meteorological report is the second in a series of reports intended to provide insights and increase understanding of the influence of atmospheric icing on aircraft operations. The focus of this report has been on the commercial AAM sector for the four metropolitan areas of Chicago, New York, San Francisco, and Los Angeles, and it tries to quantify the resulting impact of icing over these areas. A better understanding of inhibiting factors to growth will allow upcoming industry stakeholders to make more informed decisions on which factors and risks to address at which time.

The first report covered the airspace over Norway, and the resulting follow-up interest and discussions revealed a large industry stakeholder interest in the topic and highlighted a need for further investigations into icing over other geographical locations. Over the next couple of years, we expect to release new reports on the following areas:

- *Relevant metropolitan areas in North America, e.g., Miami and Toronto.*
- *Larger metropolitan areas in Europe, e.g., Berlin, Rome, and Barcelona.*
- *South American metropolitan areas, e.g., Mexico City and Rio de Janeiro.*
- *The Arctic and Northern Europe, e.g., Greenland and Iceland.*

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7 Appendix; biographies

7.1 Authors

Dr. Kim Lynge Sørensen is one of the founders and the CEO of UBIQ Aerospace. Originally from Copenhagen, Denmark, he has an 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 awarded a Ph.D. 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 postdoctoral fellow at NTNU, 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 an MSc. in electrical engineering with a special focus on robotics technology from 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, Kasper was part of a small group that founded UBIQ Aerospace. 2018, he was awarded a Ph.D. in Aerospace Cybernetics from NTNU, and in 2019, after a year as a postdoctoral fellow at NTNU, he joined UBIQ as the CTO.

Dr. Richard Hann holds a degree in aerospace engineering from the University of Stuttgart in Germany. He completed his Ph.D. on the topic of icing on UAVs at the Department of Engineering Cybernetics at 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 is one of the leading researchers in the field of UAV icing and head of the NTNU UAV Icing Lab. He also works as a head of aerodynamics 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 the 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 climatology of icing and the production of large drop icing conditions. 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.

Paul Pellicano is an aerospace engineer in the Federal Aviation Administration (*FAA*) where he is responsible for aircraft icing certification regulations and policy, research and continued operational safety. He joined the FAA in 1998 as a flight test engineer after 17 years in industry, transitioning to his current position in 2001. Paul worked with industry to develop means of compliance for the most recent part 25 and part 23 icing certification regulations. He is currently working with industry, foreign airworthiness authorities, and operational entities to address adverse weather certification and operational requirements for new and novel technology, such as unmanned aircraft, electric powered aircraft, and powered lift aircraft.

7.2 Reviewer

Rohit Goyal is an Aerospace Engineer with over 10 years of experience in emerging sectors such as Urban Air Mobility, Unmanned Aircraft Systems, Supersonics, and Commercial Space. He currently serves as the Head of Strategy at Boeing's Future Mobility group. Rohit's previous roles include Lead Economist at Joby Aviation, Strategy Leader at Uber Elevate, and Urban Air Mobility Lead at Booz Allen Hamilton. He holds a Master's in Engineering Sciences from Harvard University and specialized in Aeronautics & Astronautics at MIT.