An Initial Assessment of the Potential Weather Barriers of Urban Air Mobility

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Abstract— **Urban Air Mobility (UAM), a subset of advanced air mobility, is a concept that envisions safe, sustainable, affordable, and accessible air transportation for passenger mobility, cargo delivery, and emergency management within or traversing a metropolitan area. In recent years, several companies have designed and tested enabling elements of this concept, including; prototypes of vertical take-off and landing (VTOL) aircraft, operational concepts, and market studies to understand potential business models. While UAM may be enabled by the convergence of several factors, a number of barriers such as weather could present challenges to scaling operations. This research discusses the potential weather and public acceptance challenges for operations in adverse conditions. This paper presents a comprehensive seasonal and diurnal climatology analysis using historical observations across anticipated operational altitudes (surface – 5000 ft AGL) at ten metropolitan areas across the United States for the NASA Aeronautics Research Mission Directorate (ARMD). Public perceptions of weather-related societal barriers were evaluated through a five-city general population survey (n=1,702) where respondents were asked about their views regarding flying in a small aircraft in a variety of adverse weather conditions using a six statement 5-point Likert scale. The results of the climatology analysis found weather most favorable in Los Angeles and San Francisco, with much less favorable conditions in Denver, New York City, and Washington D.C. In the future, equipping automated vehicles, unmanned aircraft systems, and VTOLs with meteorological sensors coupled with machine learning and artificial intelligence could enhance predictive capabilities that reduce flight cancellations and delays for travelers.**

Index Terms— **Advanced Air Mobility (AAM), on-demand air mobility, barriers, eVTOL, perception, Rural Air Mobility, societal, Urban Air Mobility (UAM), vertical take-off and land (VTOL), weather.**

I. INTRODUCTION

URBAN air mobility (UAM), a subset of advanced air mobility (AAM), is a concept that envisions safe, sustainable, affordable, and accessible air transportation for passenger mobility, cargo delivery, and emergency management within or traversing a metropolitan area. A variety of built environments are being considered for these operations, ranging from small and rural communities to large megaregions [1]-[3]. As of February 2020, a number of manufacturers are designing and testing aircraft to support UAM, including approximately 250 prototypes of vertical take-off and landing (VTOL), electric, and autonomous aircraft [5]. Early UAM passenger services using traditional rotorcraft (helicopters) are already operating in Los Angeles, Mumbai, New York City, San Francisco, São Paulo, Singapore, and other markets [6]-[8].

While UAM may be enabled by the convergence of several factors (e.g., electrification, automation, and shared mobility), several challenges exist that could limit the scaling of passenger services, such as weather [1], [8]. The sensitivity of aviation to weather hazards increases notably with the decreasing size of aircraft [9]-[12]. Weather conditions, such as thunderstorms, wind shear, icing, and low visibility conditions, could pose notable safety, operational, and reliability challenges for UAM, particularly during phases of flight (i.e., takeoff, departure, transition from vertical to horizontal flight, and landing). Recognizing these potential challenges, in Summer 2020 NASA established a weather-focused working group as part of its broader AAM Community Integration Working Group. Because of the relatively low-level cruise altitude for UAM operations, all phases of flight could confront potentially critical weather challenges [1], [3], [8]. While aircraft design and technology may be able to expand the performance limits, some weather challenges are likely to remain [1], [3], [8].

Some different weather and atmospheric conditions that could impact UAM include [1], [3], [8]:

- **Ice:** Snow and ice can stick to critical surfaces (i.e., wings and rotors). De-icing systems and icephobic surfaces (currently under development) may be able to help mitigate some of these risks.
- **Visibility:** For the vast majority of piloted aircraft under instrument flight rules (IFR) conditions, pilots still require to visually observe the landing environment. In the future, autonomous aircraft may be able to land in a greater variety of low visibility conditions, however, minimums may still be required given potential technological limitations of the landing systems.
- **High Winds:** High winds and wind gusts can create a number of challenges for UAM operating at low altitude and high-density built environments. High-rise buildings can also create canyon effects that produce unpredictable wind environments in urban centers.

An exploratory study [3] of UAM found that no more than 16% of aggregate operational time will be impacted by weather. However, the study also notes that particular markets, such as New York City and London, could have greater weather constraints. As such, additional study is needed to understand

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the potential impacts of weather on UAM operations across a greater sample of metropolitan areas. Another exploratory study [13] examined consumers' willingness to fly on autonomous air taxis in various weather conditions, topography, flight time, and population densities. [13] found that consumers may be more willing to fly in good weather conditions, over land (instead of water), and on shorter flights. [14] estimates the safety considerations required to account for weather in vertiport design. [15] proposes dynamic geofencing - a moving region of reserved airspace for an aircraft - could be an air traffic management strategy to prevent aircraft from flying in airspace impacted by weather.

Existing studies on the potential impacts of weather on UAM operations are limited, often due to a variety of aircraft under development with different performance limitations. Additionally, the proprietary nature of these aircraft concepts results in limited publicly available information about their performance envelope (i.e., design capability in terms of airspeed, weight, cruise altitude, density altitude, etc.). Furthermore, studies that have examined the impacts of weather on UAM tend to focus on case studies of particular markets rather than multi-city analyses. This paper attempts to overcome these limitations and advance the state of the practice by providing a framework for multi-city UAM weather analysis in the U.S. This paper is informed by existing literature and expert interviews on probable aircraft performance limitations to understand potential UAM weather opportunities and challenges for passenger mobility using small (approximately four to six seat) piloted, remotely piloted, and autonomous aircraft [16], [17]. This methodological framework is intended to be broad enough to accommodate a variety of small aircraft types currently under development. More specific analysis would be needed to determine the suitability of a specific aircraft.

This paper is organized into four sections. The first section presents a methodological framework that the authors used for conducting a comprehensive seasonal and diurnal[1] climatology analysis. The methodology also discusses the focus groups that were used to develop a general population survey to ask respondents about their views regarding flying in a small aircraft in a variety of adverse weather conditions. The second section presents the findings of the climatology analysis for density altitude, weather impacted hours, and ten U.S. cities capturing meteorological variability. While these results are organized according to regional geography, it is important to remember that the results are specific to each city and not generalizable for an entire region. In the third section, the findings from the general population survey are presented. The paper concludes with recommendations for UAM service providers and a discussion of how sensors, connected infrastructure, predicative analytics could improve meteorological monitoring and more timely weather guidance for UAM operations.

II. METHODOLOGICAL APPROACH

A. *Seasonal and Diurnal Climatology Analysis*

As part of a market assessment for the NASA ARMD, the authors used a multi-method approach comprised of a comprehensive seasonal and diurnal climatology analysis and a general population survey to study the potential challenges weather may pose to UAM operations and societal acceptance, respectively. This research was part of a broader UAM market study guided by NASA and a 30-member strategic advisory group (SAG) representing transportation, weather, and aviation, and other expertise on the selection of urban areas for detailed study. SAG members included senior leaders and subject matter experts from the Federal Aviation Administration (FAA), NASA, National Transportation Safety Board (NTSB), North Carolina Department of Transportation, New York City, Los Angeles, Los Angeles World Airports, International Civil Aviation Organization (ICAO), and numerous startups, manufacturers, and research institutions. In consultation with the SAG, ten U.S. urban areas (Dallas, Denver, Honolulu, Houston, Los Angeles, Miami, New York City, Phoenix, San Francisco, Washington D.C.) were selected for detailed study as part of the broader UAM market study. The selection process included numerous considerations, such as anticipated early adopter markets where immediate research was needed, markets identified as infrastructure ready, demographic variability, and markets that could present a variety of challenges to adoption (i.e., market economics, opposition to aviation noise, less favorable weather, etc.). The ten cities approved by NASA and the SAG for detailed study balances numerous considerations, not only for this weather analysis but other aspects of the broader NASA market study. While the ten cities selected reflect a variety of geographies and weather patterns, additional research is needed across a larger sample of cities, built environments, and climates.

Next, available historical weather data were obtained from archives of the FAA's Aviation System Performance Metrics (ASPM) data and NOAA's Meteorological Assimilation Data Ingest System (MADIS) focusing on those collected in and near focus urban areas. The researchers focus was on regularly collected weather observations including Meteorological Aerodrome Report (METAR), vertical soundings, and pilot reports (PIREP) for this analysis. METAR are point observations collected hourly at the surface, most commonly at airports, and capture a wide range of conditions, including temperature, wind direction and speed, sky cover (low ceilings/visibility), and present weather (e.g., thunderstorms, rain, snow). Vertical soundings are generated from weather balloons that are launched twice a day from a fixed location, in morning (12Z) and afternoon (00Z) and provide conditions aloft, which would be experienced during UAM flight or at an elevated vertiport. Data collected from these soundings include temperature, pressure, dew point, and wind speed and direction at multiple altitudes from the surface to about 65,000 ft. Pilot reports (PIREPs) are generated whenever a pilot encounters

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[1] Diurnal variation is the variation in weather that occurs during the same day.

weather conditions that they deem impactful, such as low-level wind shear or turbulence. PIREPS used in this analysis were constrained to altitudes below 5,000 ft to align with anticipated UAM operational altitudes. These are not collected at a regular time interval, so they are used as a supplemental source of weather impacts to augment signals observed from the METAR and vertical soundings. It is important to note that these data are being used to generate a high level, annual and seasonal, climatology of conditions. Further study would be needed to assess higher frequency variability impacts, such as minute-to-minute evolution in weather conditions.

An evaluation of the spatial extent and distribution of observation locations relative to the focus urban areas was conducted to assess how representative these data are of conditions and variability within the urban area. The METAR surface and vertical sounding observation locations overlap well with several of the target urbanized areas but may not be fully representative of conditions in all urban areas. In most of the Eastern U.S. and Texas target urban areas, these observation locations are distributed evenly across the region while in some locations such as Miami and Houston, the observations only capture conditions in one portion of the region. Furthermore, in some focus urban areas such as Denver, vertical sounding observations are collected outside of the urban area and may not fully represent conditions within the urban area (i.e., urban heat islands or areas having higher average temperature than its rural surroundings due to greater absorption, retention, and generation of heat by buildings, pavements, and human activities). As such, observations from these data sources may not be entirely representative of the spatial extent and variations in weather conditions within a metropolitan area. Reliable and higher resolution data is needed to more fully examine potential weather challenges. Despite these limitations, these observations provide baseline historical conditions in the target urban areas to assess UAM weather barriers.

Weather conditions that could impact UAM operations may vary notably both diurnally and seasonally in many of the target urban areas, so the researchers stratified the climatology by hour of the day and meteorological season – Winter (Dec, Jan, Feb), Spring (Mar, Apr, May), Summer (Jun, Jul, Aug), and Fall (Sep, Oct, Nov). The analysis focused on the anticipated operational window of 7AM to 6PM local time.

For METAR surface observations, statistics were computed over a 7-year historical period (2010-2017), such as average temperature and frequency of conditions such as thunderstorms and non-Visual Flight Rules (VFR), which includes Low Instrument Flight Rules (LIFR), Instrument Flight Rules (IFR), or Marginal Visual Flight Rules (MVFR) conditions, for each hour of the operational window and each season. These statistics were first calculated and evaluated at each METAR location for an urban area to enable assessment of variability in adverse conditions at different locations within the urban area. Next, statistics across all METAR stations were calculated and aggregated to analyze the seasonal variability in conditions across the urban area.

Since vertical sounding observations are only collected twice a day, the researchers computed seasonal averages across a 5-year historical period (2013-2017) for each of these two times (12Z and 00Z) at all target urban areas. Observations are collected at irregular vertical intervals as the balloon ascends, so average conditions in 500 ft intervals were calculated to ensure sufficient sample size. Density altitude was computed from seasonal average conditions in the lowest available vertical bin at all urban areas to characterize lift conditions at vertiports. Average winds were generated by calculating the average North-South and East-West wind vector components of all historical winds in each altitude bin.

PIREPS were used as supplemental observations to augment results from the surface and vertical sounding observations due to their ad hoc collection. These were isolated across a 3-year historical period (2015-2017) over or near the focus urban areas local airport codes in the reports. Within each urban area, the researchers computed the percentage of reports with each type of reported weather to identify which conditions were most prevalent (i.e., freezing temperatures, low ceilings, rain, turbulence, winter weather, low-level wind shear, etc.). Across all urban areas, low ceilings and turbulence were the most frequently reported conditions with low-level wind shear being reported somewhat frequently at several urban areas, such as Denver and San Francisco.

After generating detailed statistics on historical weather conditions individually, the researchers calculated the overall average number of hours that UAM operations could potentially be significantly impacted based on the underlying conditions. The goal of capturing impacted hours is to provide a consolidated metric for weather impacts during the UAM operational day at each urban area. The impacted hours were generated using METAR surface observations as they provide the highest temporal resolution (hourly) of all the data sources. While these hourly statistical observations capture high level tendencies, a methodological limitation is the inability to capture finer-scale temporal variability (such as minute by minute weather changes).

The researchers then defined "impact scores" for each weather condition captured in METAR observations, from 1 (minimally impactful, little reduction in operations) to 10 (significantly impactful, potential cessation of operations). Based on the researchers' expertise in aeronautical weather, a study conducted by MITLL for the FAA on UAS weather gaps [18], coupled with input from the strategic advisory group, the researchers defined scores (Table I) intended to capture potential impacts across a wide range of UAM operations (without making specific aircraft assumptions or assumptions of piloted versus autonomous flight). These scores were assigned individually and combinatory impaction (e.g., rain and wind) are captured in quantification of "impacted hours", described later in this section. These scores should be considered somewhat general and capture range of potential impacts to various aircraft types. They could be further refined for specific aircraft types. However, vertical wind shear is an important condition that will likely impact UAM operations which cannot be directly quantified from surface observations. These impact scores could be extended by leveraging higher temporal resolution vertical data, such as airborne observations from commercial aircraft.

The researchers then computed the average impact score at each hour of the operational day for each season at all target urban areas, based on conditions, including combinations of conditions, that occurred historically during that hour. To define an hour of the operational day as “impacted”, the researchers needed to define an average impact score threshold. The researchers evaluated variability of the average impact score distributions, as well as the impact scores themselves, and determined that an average impact score threshold of three provided a robust delineation between minimal and significant potential impacts to UAM operations. This threshold could be further refined with additional analysis, and also through application of specific assumptions about UAM operations (e.g., aircraft type). If an average impact score for any hour of any season exceeded three, that hour was considered to be potentially impacted by weather, or an “impacted hour.” The number of impacted hours was summed across the operational day for each season.

TABLE I

IMPACT SCORES FOR EACH WEATHER CONDITION FROM METAR

Weather Condition	Score	Weather Condition	Score
Drizzle	1	Wind 20 - 25 kts	7
Rain	1	Smoke (<3 sm)	7
MVFR Ceiling	1	LIFR Ceiling	7
Haze	1	Non-VFR Visibility	7
Ice Crystals	1	Wind ≥ 25 kts	8
Sand Whirls	1	Sleet	8
Sand	2	Squalls	8
Snow Grains	2	Fog	8.5
Temp ≤ 32°F	3	Freezing Fog	8.5
Temp ≥ 100°F	3	Freezing Drizzle	9
Non-VFR Ceiling	4	Thunderstorms	9
Dust	5	Dust Storm	10
Snow	5	Funnel Cloud/Tornado	10
Sandstorm	5	Freezing Rain	10
Wind 15 - 20 kts	5	Hail	10
Mist (vis >= 5/8 sm)	6	Volcanic Ash	10
Snow Pellets	6		

However, a key limitation with this approach is that impact scores (and weather impacted hours) are based only on surface observations and cover a range of operational scenarios (i.e., piloted and autonomous flight). In the future, as aircraft performance limitations become available for electric, vertical take-off and land (VTOL), and autonomous aircraft, this analysis could be refined by analyzing specific scenarios and performance limitations (e.g., a piloted electric VTOL aircraft operating in a specific market). In spite of these limitations, this study provides a baseline for analyzing potential UAM weather barriers associated with a variety of aircraft and operations.

B. *Focus Groups and General Population Survey*

Research on the potential societal barriers of an emerging technology is important to understanding the potential viability of the technology from a societal perspective, and opportunities and challenges from a market perspective. In addition to the weather analysis, the researchers conducted two focus groups in Los Angeles and Washington D.C. in June 2018 followed by a five-city exploratory general population survey in August 2018. Focus group respondents were recruited using paper flyers and online forums (i.e., Craiglist, Nextdoor, Facebook, Twitter, etc.). Findings from the focus groups were used to inform the development of the general population survey, including survey questions that asked about willingness to fly in various weather conditions. Due to the lack of certified eVTOL aircraft at the time of this research, a notable limitation of the focus groups and survey is the lack of personal experience with UAM in actual weather conditions. Survey respondents were recruited using a professional survey firm (Qualtrics) and screened based on their gender to obtain a more uniform distribution of male and female respondents and based on the metropolitan region in which they resided. The completed survey target included approximately 350 respondents each from Houston, Los Angeles, New York, the San Francisco Bay Area, and Washington, D.C with a total of 1,702 respondents. For each region, we aimed to collect responses that were a fair approximation of the demographic distribution of the general population of each metropolitan area studied. The metropolitan regions were selected in consultation with the strategic advisory group to capture variability in demography, geography, weather patterns, traffic characteristics, and the built environment. The survey explored a variety of topics, including how weather conditions may impact the willingness to fly of potential UAM travelers.

The survey questions employed a “willingness to fly” scale adapted from [19] to measure differences in passenger perceptions. The scale consists of six statements to be rated using a 5-point Likert scale ranging from -2 (strongly disagree) to 2 (strongly agree) with a neutral option (0). These questions asked if potential UAM travelers would feel 1) willing; 2) confident; 3) happy; 4) safe; 5) afraid; and 6) concerned flying in rain, fog/low visibility conditions, snow, light turbulence, and extreme (hot and cold) exterior temperatures.

Survey-based research is a useful technique for gathering a wide range of data about a population such as the attitudes, behavior, and characteristics of the survey population. Surveys are relatively easy to administer and offer flexibility in data collection. However, limitations exist with this methodological approach. For example, responses to survey questions are self-reported and are subject to respondent bias. It is also possible that a survey questionnaire may not evoke truthful responses from the sample population (Ponto, 2015). Another possible source of error could occur due to priming and survey questions must be carefully ordered and worded to prevent influencing how people respond to subsequent questions. Finally, it is challenging for individuals to respond to an innovation without having direct experience with it. This impacts a respondent’s ability to answer questions based upon limited to no experiential understanding. These survey results likely reflect this limitation. While most respondents had some familiarity with aviation weather in the context of commercial flight, the lack of consumer familiarity with UAM aircraft represents a key limitation of this methodology. More research is needed to understand the impacts of weather on traveler willingness to fly in actual small electric vertical take-off and landing (eVTOL) aircraft.

III. WEATHER ANALYSIS FINDINGS

Weather analysis can be a useful tool to help pilots, service providers, and airspace managers plan for UAM and understand operational limitations due to meteorological conditions. This section describes the results, focusing on density altitude, weather impacted hours, and other key indicators, such as high historical frequency of potentially impactful weather conditions, variability in conditions within an urban area, diurnality/seasonality, and the average number of impacted hours. The researcher's evaluated the spatial distribution of reported conditions in each urban area to augment signals observed from surface and vertical soundings because the sample size of historical PIREPs was not sufficient to evaluate seasonal or diurnal variability in conditions. Summary results for density altitude and weather impacted hours are presented for all regions followed by a regional discussion of the findings.

A. *Density Altitude*

Density altitude is the altitude relative to standard atmospheric conditions at which the air density would be equal to the indicated air density at the place of the observation (reported as height above mean sea level) [20]. In aviation, density altitude is one measure for assessing an aircraft's aerodynamic performance under certain weather conditions. Indicated airspeed, true airspeed, power delivered by aircraft engines are affected by the density and composition of the atmosphere [20]. In other words, air density can impact the lift of wings, efficiency of propellers and rotors, and the power output of engines. For example, aircraft taking off from locations with conditions of low air density due to high temperatures and high airport elevations (known as "hot and high") can cause aircraft to: 1) accelerate more slowly due to reduced power output; 2) need to obtain higher true airspeeds to attain the same amount of lift; and 3) climb more slowly due to reduced power and lift [20].

The average density altitude for all target urban areas in each season, calculated from conditions in the lowest altitude bin of the vertical sounding data along with the field elevation from which the observations were taken is shown in Table II.

TABLE II
AVERAGE SEASONAL DENSITY ALTITUDE FOR FOCUS URBAN AREAS

Urban Area	Field Elev. (ft)	Spring (ft)	Summer (ft)	Fall (ft)	Winter (ft)
Dallas	561	682	2055	786	-460
Denver	5285	5742	6974	6025	4759
Honolulu	98	1039	1498	1248	885
Houston	33	436	1342	527	-349
Los Angeles	397	3	30	36	-9
Miami	16	779	1281	1026	484
New York City	65	-968	645	-618	-1976
Phoenix	2464	3660	4614	3830	2641
San Francisco	10	-115	343	217	245
Washington D.C.	305	-152	1264	27	-1384

Density altitude is greatest for all urban areas during summer, when temperature is typically highest. Phoenix has the highest average summer density altitude relative to surface elevation above sea level (~2000 ft) that could impact UAM takeoff and lift capability. Average density altitude is also about 1000-2000 ft above surface elevation in Miami during summer and fall, and Dallas, Denver, and Houston during the summer.

B. *Weather Impacted Hours*

The average number of weather impacted hours during the UAM operational day (7AM – 6PM Local Time) was computed for each season across all focus urban areas [4]. Table III shows the weather impacted hours and the average across all seasons.

TABLE III
AVERAGE NUMBER OF WEATHER IMPACTED HOURS FOR ALL TARGET URBAN AREAS BY SEASON

Urban Area	Winter (hrs)	Spring (hrs)	Summer (hrs)	Fall (hrs)	Average (hrs)
Dallas	11	12	3	0	6.5
Denver	12	12	4	3	7.75
Honolulu	0	7	9	6	5.5
Houston	9	11	0	0	5
Los Angeles	2	1	2	1	1.5
Miami	0	0	0	0	0
New York City	12	12	0	8	8
Phoenix	0	0	5	0	1.25
San Francisco	3	6	6	4	4.75
Washington D.C.	12	12	0	0	6
Average	6.1	7.3	2.9	2.2	

Based on the average values across the seasons, approximately half of the UAM operational day would potentially be impacted by weather on average at most target urban areas including Dallas, Denver, Honolulu, Houston, New York City, and Washington D.C. Additionally, there were a high number of weather impacted hours (sometimes greater than half of the UAM operational day) during the winter and spring in Dallas, Denver, and Houston.

Most urban areas experienced the fewest impacted hours during the summer and fall (with the exception of Honolulu and Phoenix). In Phoenix, almost half of the operational day could potentially be impacted by adverse weather during summer due to the high frequency of several impactful conditions (i.e., thunderstorms and high temperatures, etc.). In Honolulu, the high frequency of strong winds through most of the operational day during summer results in a high number of weather impacted hours during summer. Despite historical occurrence of adverse conditions such as thunderstorms, the number of weather impacted hours in Miami was zero for all seasons. This is due to the fact that the underlying frequency of thunderstorms was sufficiently low that the average impact scores for all hours of the UAM operational day fell below the threshold of 3. However, a limitation is the underlying frequency of occurrence is different for all phenomena, with smaller values expected for small scale, short-lived conditions like thunderstorms.

C. *The Pacific Region*

Overall, the analysis concluded that weather conditions are favorable for UAM operations in Honolulu, Los Angeles, and San Francisco. In these cities, most PIREPs were due to turbulence, located mostly over the ocean, and low ceilings, consistent with findings from METAR observations. Additionally, the analysis generally showed that inland areas had lower frequency of non-VFR conditions than coastal areas.

In the Los Angeles, weather conditions are mostly favorable for UAM operations, though non-VFR conditions are somewhat frequent in morning, particularly during summer.

There was also variability within urban area during summer, where historical non-VFR frequency was above 50% in early morning at Los Angeles International Airport (LAX) while only about 20% at Van Nuys (VNY) (Fig. 1).

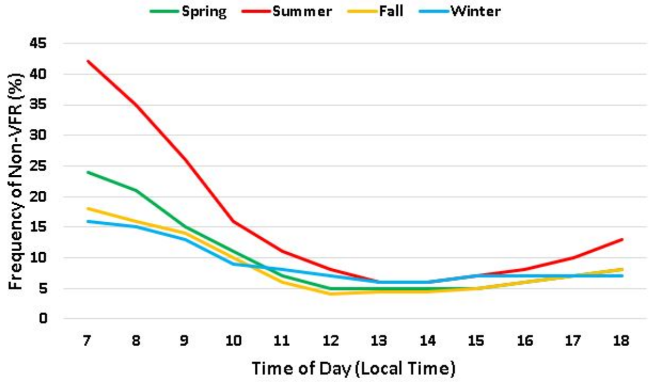

Fig. 1. Time series of frequency of Non-VFR conditions at LAX and VNY (aggregated) by season in Los Angeles urban area.

The analysis also identified variability in conditions within the San Francisco urban area, which frequently experiences non-VFR conditions and winds above 20 knots (kts) in most seasons. The frequency of winds above 20 kts is significantly greater at San Francisco International Airport (SFO) than Oakland International Airport (OAK) in all seasons except for winter. This suggests that wind conditions are more favorable for UAM in the eastern portion of the urban area during afternoon hours. Non-VFR conditions also have a high historical frequency during morning hours, exceeding 60% before 8 am Local Time in summer. In Honolulu, surface winds above 20 kts are the only potentially impactful condition with a relatively high frequency of occurrence (9-10%) in early afternoon during spring and summer.

D. *The Southwest Region*

In the Southwest cities studied (Dallas, Houston, and Phoenix), frequent thunderstorms, non-VFR conditions, and vertical wind shear conditions pose potential challenges for UAM operations in most seasons. In Houston, the analysis identified some variability in non-VFR condition frequency within the urban area. These conditions are most frequent during morning in winter and spring overall, but have a higher frequency at George Bush Intercontinental Airport (IAH) (over 35%), in the northern part of the urban area, than at William Hobby Airport (HOU) (20%) which is in the southern portion of the urban area. A review of the PIREPS in the Houston urban area shows that the primary weather condition reported by pilots is low visibility. High surface air temperatures, which may impact passenger comfort, are possible in summer and early fall. Thunderstorms were also frequent in early afternoon during summer, which would impact UAM operations. The research also shows a strong low-level jet, or altitude band with strong winds, typically present around 2500 feet in morning during winter along with strong winds near 5000 feet.

Average weather in the Dallas urban area was similar to Houston, with high temperature, non-VFR conditions, thunderstorms, and strong low-level jet being the most frequent potentially impactful conditions to UAM. The frequency of non-VFR conditions during morning in fall and summer was higher in Dallas than Houston, but still less frequent than in winter and spring. The analysis also found that thunderstorms were more common during afternoon in spring than in Houston, possibly due to strong cold fronts that are frequent during the spring.

Phoenix experiences several weather conditions on average that may be impactful to UAM operations, including high temperatures, strong winds (Fig. 2), and thunderstorms. These unfavorable conditions occur most frequently during afternoon in summer. Most PIREPS in Phoenix were due to turbulence and were uniformly distributed spatially across the urban area.

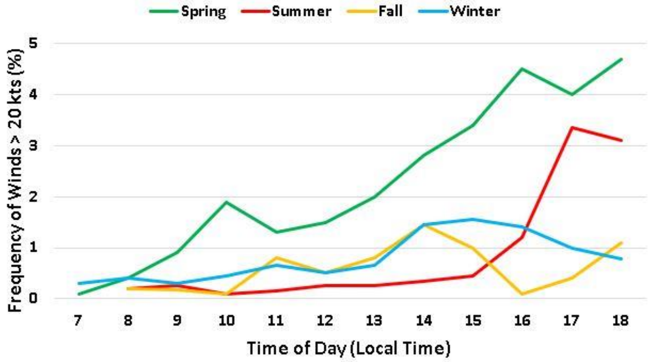

Fig. 2. Frequency of winds above 20 kts by season in the Phoenix urban area.

E. *The Eastern Seaboard*

Average weather conditions were found to be less favorable in the cities studied along the Eastern Seaboard (i.e., New York City, and Washington D.C.) than the Pacific cities examined (i.e., Los Angeles, and San Francisco). In Washington, D.C., thunderstorms and non-VFR conditions are the most frequent potentially impactful weather. Non-VFR conditions are on average most common in the early morning during all seasons while thunderstorms occurred most often in afternoon during summer. Most PIREPs were due to turbulence and low ceilings, the majority of which were reported while departing out of Dulles International Airport (IAD) in the western portion of the urban area.

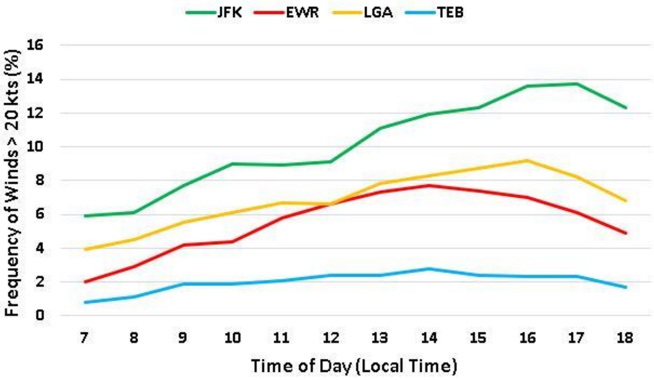

Fig. 3. Time series of frequency of winds above 20 kts in winter by METAR location in the New York City metropolitan area.

Similarly, several adverse conditions were frequent in the New York City area for most hours and seasons, which included non-VFR conditions, winds above 20 kts, and rapid changes in wind speed with altitude, or vertical wind shear (Fig. 3). Variability in strong winds was observed within the urban area, with John F. Kenned International Airport (JFK) (in the borough of Queens) experiencing the highest frequency of winds above 20 kts during afternoon (~14%) while a significantly lower frequency of occurrence (~2%) was observed at Teterboro Airport (TEB) (northern portion of urban area in New Jersey) (Fig. 3). Across the urban area in aggregate, non-VFR conditions are frequent (20-25%) during all seasons in early morning. Wind shear was also observed during morning in winter, with average wind speed increasing from only a few knots at the surface to almost 20 kts around 1000 ft altitude which could impact operations during takeoff and in flight. Similar to Washington, D.C., most PIREPs in the New York urban area indicated turbulence and low ceilings.

In Miami, overall average weather conditions were favorable for UAM. Thunderstorms occurred frequently during early afternoon in summer and fall, while non-VFR conditions were somewhat common during winter in the early morning hours.

F. *The Rocky Mountain Region*

The analysis suggests that UAM could have the greatest weather challenges in Denver due to lower temperatures, strong winds, and thunderstorms. However, additional research is needed to study additional cities, such as Boise and Salt Lake City.

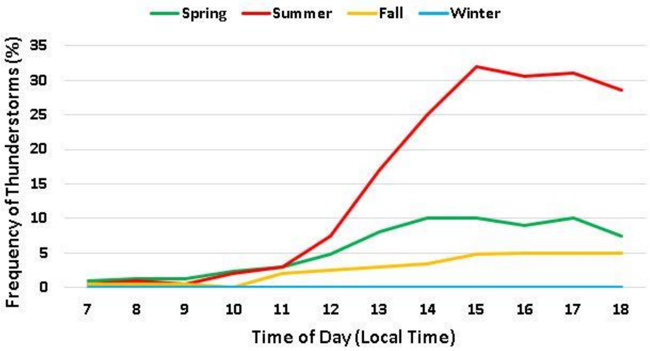

Fig. 4. Time series of frequency of thunderstorms by season in the Denver area.

In Denver, average weather conditions are unfavorable for UAM operations during most hours and seasons. Cold temperatures (below freezing) which may reduce passenger comfort and influence battery range/life are possible during fall, winter, and spring especially in the morning hours. Non-VFR conditions are also somewhat frequent (15%) during the morning across all seasons, with lowest frequency occurring during summer. Thunderstorms and strong winds are common during afternoon in summer, which could compromise safety of UAM operations (Fig. 4). Strong average winds aloft (5000 ft) were also observed during all seasons on average, which could influence UAM mission duration and vehicle spacing (for large scale operations). Denver is also one of the few focus urban areas where PIREPs were generated for all types of weather conditions. Turbulence and wind shear were the most frequently reported conditions and were distributed uniformly across the urban area spatially.

IV. POTENTIAL SOCIETAL BARRIERS: WEATHER AND CONSUMER WILLINGNESS TO FLY

The researchers conducted a five-city general population survey administered online to 1,702 respondents in August 2018. After briefly introducing survey respondents to the concept of UAM through a written definition and an introductory video, respondents were asked to answer questions about their willingness to fly as a passenger in a UAM aircraft in a number of situations, including a variety of adverse weather conditions, such as: rain, fog/low-visibility, snow, wind with light turbulence, and extreme hot and cold exterior temperatures. This section reviews respondent demographics and summarizes the weather findings from the survey.

A. *Respondent Demographics*

The survey collected basic demographic information of respondents including: household income, education, age, race/ethnicity, and gender.

TABLE IV
SURVEY RESPONDENT DEMOGRAPHICS COMPARED TO THE 2016 AMERICAN COMMUNITY SURVEY (ACS)

Household Income (USD)	2016 ACS	Survey Respondents
Less than $10,000	6%	5%
$10,000 - $14,999	4%	4%
$15,000 - $24,999	8%	8%
$25,000 - $49,999	18%	16%
$50,000 - $74,999	16%	16%
$75,000 - $99,999	12%	14%
$100,000 - $149,999	16%	13%
$150,000 - $199,999	8%	7%
$200,000 or more	11%	9%
Education	2016 ACS	Survey Respondents
No high school diploma	16%	1%
High school graduate (or equivalent)	22%	13%
Some college (no degree)	18%	5%
Associate's / 2-year degree	7%	10%
Bachelor's / 4-year degree	23%	36%
Graduate or professional degree	15%	32%
Age	2016 ACS	Survey Respondents
18 – 24 years	9%	9%
25 – 34 years	15%	26%
35 – 44 years	14%	18%
45 – 54 years	14%	13%
55 – 64 years	12%	16%
65 – 74 years	7%	17%
75+ years	6%	5%
Race	2016 ACS	Survey Respondents
Hispanic or Latino	30%	10%
White or Caucasian	41%	55%
Black or African American	14%	16%
American Indian or Alaskan Native	0%	1%
Asian	13%	12%
Native Hawaiian or Pacific Islander	0%	0%
Other	0%	2%
Two or More Races	2%	2%
Gender	2016 ACS	Survey Respondents
Female	51%	57%
Male	49%	43%

Table IV provides a summary of each of these demographic categories across all respondents as well as American Community Survey (ACS) data to compare the respondents to the general population. In general, the respondents represented the distribution of household income levels across the cities, with slight underrepresentation of the highest income brackets (respondents with more than $150,000 annual household income). In terms of educational attainment, responses were skewed toward those who had attained a bachelor's or graduate degree (36% with a bachelor's degree and 32% with a graduate degree or currently in graduate school). Only 1% of the respondent population had less than a high school degree, while the average across the cities in the 2016 ACS survey was closer to 16%. Overall, respondents reflected the 2016 ACS age distribution. The distribution is slightly biased toward a younger demographic (those 25 to 34 years of age), but there is also a slight overrepresentation of respondents in the 65 to 74 age group (17% in the survey population versus 7% in the general population). With respect to race and ethnicity, approximately 55% of respondents were White/Caucasian. Hispanics or Latinos were underrepresented by the survey population at approximately 10% of respondents.

B. Survey Findings

The survey found that weather conditions impacted the willingness of a respondent to fly in a UAM aircraft. Using the 5-point Likert willingness to fly scale, the survey findings provide early insight into weather conditions that travelers enjoy flying, weather conditions that travelers are willing to fly, and weather conditions that could create traveler apprehension (i.e., general concerns, unease about safety, and fear of flying). While a notable portion of respondents (more than 50% in each of the weather scenarios, and as high as 81% for hot and cold conditions) were willing to fly in a UAM aircraft under adverse weather conditions, respondents reported increased levels of fear and concern associated with a number of weather conditions. In particular, survey respondents were apprehensive toward flying in rain, snow, low visibility, and turbulence, while they tended to be indifferent to hot and cold weather conditions. Respondents were the most afraid of snow (54%), fog/low visibility (57%), and turbulence (52%) (Fig. 5). Respondents reported much lower levels of fear associated with flying extreme (hot or cold) exterior temperatures (29%) Aggregate responses for all five cities using the willingness to fly scale applied to rain, fog/low-visibility conditions, snow, wind/light turbulence, and extreme hot and cold temperatures are shown in Fig. 5.

The survey results suggest that respondents may not have apprehensions about flying in extreme hot or cold temperatures, perhaps due to the lack of familiarity of the risks associated with these conditions by the public. The researchers also conducted a cross-tab analysis looking at the impact of specific weather conditions on the fear of flying in four weather conditions (rain, fog/low-visibility, snow, and wind with light turbulence) in five U.S. cities (Houston, Los Angeles, New York City, San Francisco, and Washington D.C.).

In general, the comparative analysis across all five cities did not reveal many notable differences in fear or apprehension of flying in a variety of adverse weather conditions (Table V). A flew slight variations were identified in New York City, San Francisco, and Washington D.C., specific to a few weather conditions. In Washington D.C., respondents reported slightly lower levels of fear and apprehension flying in the rain. In the San Francisco Bay Area, respondents reported slightly higher levels of apprehension about flying in snow, fog, and low visibility conditions. With respect to wind and light turbulence, respondents in New York City reported slightly higher levels of apprehension whereas respondents in Washington D.C. reported slightly lower levels of fear.

While the survey collected some data on respondent experience with aviation and frequency of flight in commercial, aircraft, regional aircraft, and rotorcraft; specific conclusions could not be drawn from aviation experience and perceptions toward UAM weather conditions. The experience with weather in commercial and regional aircraft can be different from UAM aircraft due to the larger aircraft size and higher flight altitudes. Additionally, the sample of respondents with prior passenger experience flying helicopters was too small for statistically significant results. While the survey offers exploratory insight into potential passenger concerns using UAM in different weather conditions, additional research is needed to understand experiences with small, novel aircraft in a variety of weather conditions through virtual reality, simulators, and actual flights.

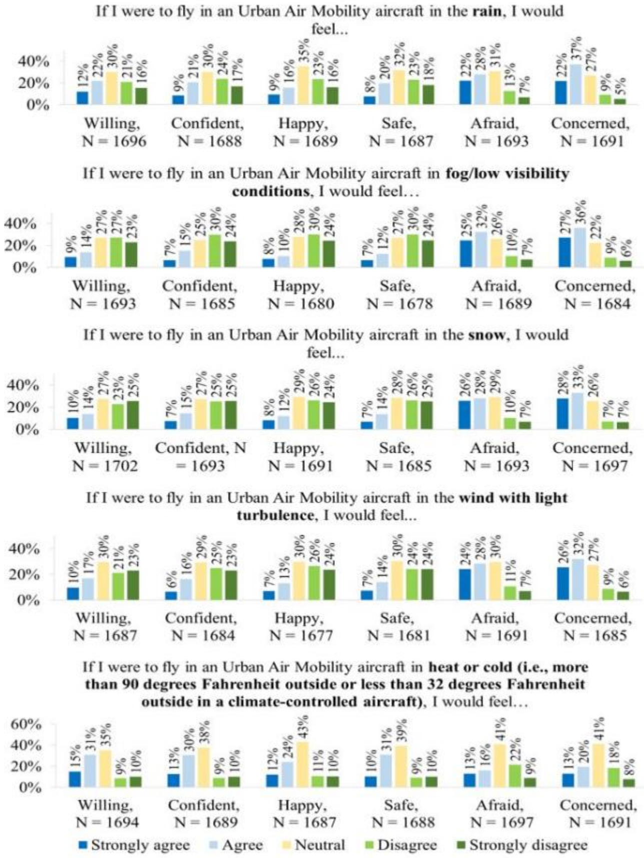

Fig. 5. Feelings toward flying in a variety of UAM weather conditions.

While many Americans have experience with commercial aviation, the impacts of these various weather conditions on feelings of comfort and safety may be magnified because the aircraft anticipated for UAM will be much smaller than most existing fixed-wing regional commercial aircraft. Additionally, there could be variations based on actual experience with a variety of UAM aircraft types and sizes. For these reasons, it is challenging for individuals to respond to survey questions about an aircraft or service that they do not have direct experience with. This impacts a respondent's ability to answer questions based upon limited to no experiential understanding. These survey results likely reflect this limitation. The lack of consumer familiarity with existing and emerging UAM aircraft represents a key limitation of this methodology. As new aircraft become certified and placed into service, more research will be needed to understand the impacts of weather on traveler willingness to fly in actual aircraft used to provide UAM service.

TABLE V
FEAR OF FLYING IN UAM IN A VARIETY OF WEATHER CONDITIONS IN FIVE U.S. CITIES

If I were to fly in an Urban Air Mobility aircraft in this condition, I would feel **afraid.**				
HOUSTON, TX				
	Rain, N=340	Fog/Low Visibility, N=340	Snow, N=341	Wind with Light Turbulence, N=341
Strongly agree	23%	25%	23%	23%
Agree	24%	31%	24%	29%
Neutral	28%	24%	32%	28%
Disagree	17%	11%	14%	12%
Strongly disagree	9%	9%	7%	8%
LOS ANGELES, CA				
	Rain, N=337	Fog/Low Visibility, N=337	Snow, N=340	Wind with Light Turbulence, N=338
Strongly agree	23%	25%	27%	25%
Agree	29%	34%	26%	29%
Neutral	30%	25%	29%	30%
Disagree	9%	8%	9%	9%
Strongly disagree	8%	8%	8%	9%
NEW YORK CITY, NY				
	Rain, N=338	Fog/Low Visibility, N=340	Snow, N=333	Wind with Light Turbulence, N=340
Strongly agree	25%	29%	26%	30%
Agree	27%	27%	26%	26%
Neutral	29%	26%	31%	27%
Disagree	13%	11%	10%	12%
Strongly disagree	5%	7%	7%	5%
SAN FRANCISCO BAY AREA, CA				
	Rain, N=339	Fog/Low Visibility, N=336	Snow, N=336	Wind with Light Turbulence, N=333
Strongly agree	21%	23%	26%	23%
Agree	31%	37%	35%	31%
Neutral	32%	25%	27%	30%
Disagree	9%	10%	7%	10%
Strongly disagree	6%	4%	7%	6%
WASHINGTON, D.C.				
	Rain, N=338	Fog/Low Visibility, N=335	Snow, N=333	Wind with Light Turbulence, N=338
Strongly agree	17%	21%	26%	21%
Agree	28%	31%	26%	27%
Neutral	35%	30%	31%	34%
Disagree	14%	10%	10%	11%
Strongly disagree	6%	8%	7%	8%

V. CONCLUSION

In the future, UAM could be one of the most disruptive transportation technologies to impact communities since the automobile. However, the ability for UAM to scale operations will be highly dependent on the ability to provide highly dependable and consistent service with minimal delays. Weather and community acceptance could pose notable barriers for mainstreaming UAM.

Based on the climatology analysis, this study concludes most favorable weather is along the Californian coast (i.e., Los Angeles and San Francisco), with much less favorable conditions in Denver, New York City, and Washington D.C. Average weather conditions were found to be less favorable in Dallas, Houston, New York, Phoenix, and Washington D.C. with higher frequencies of non-VFR conditions, high winds, and vertical wind shear that could pose potential challenges for UAM operations in most seasons. The analysis shows that UAM could have the greatest weather challenges in Denver due to lower temperatures, strong winds, and thunderstorms.

Due to the variability of weather conditions across different regions of the U.S., this exploratory study suggests that aircraft manufacturers and UAM service providers may consider mixed fleets of aircraft with different performance capabilities that are able to maximize operational capability in different weather conditions or mixed fleets that optimize flight performance for different regions of the U.S.

Timely and actionable weather guidance will be necessary to support eVTOL flight operations in urban environments. For pilots and UAM service providers, weather go/no-go forecasting that enables travelers to avoid UAM in advance when adverse weather conditions are anticipated will be key. Leveraging weather forecasting to preemptively route travelers to non-aerial modes of urban transportation prior to commencing their journey could reduce traveler disruptions associated with flight delays and cancellations. Improving safety and reducing operational impacts due to adverse weather conditions will be key to building community acceptance of urban air mobility as a safe, dependable, and convenient transportation option. As such, meteorological observation and prediction will have to be upgraded to support eVTOLs and UAM to reliably operate in most weather conditions.

While current weather observation methodologies and available infrastructure under samples the airspace in and immediately above urban centers, this study provides a valuable baseline on historical adverse conditions in the ten target urban areas (four regions) that weather barriers to UAM can be assessed. In the future, equipping automated vehicles, unmanned aircraft systems (i.e., drones), and eVTOLs with meteorological sensors connected through a 5G network could provide improved real-time weather data. This improved real-time weather data, coupled with artificial intelligence and machine learning could improve weather forecasting and predictive capabilities that reduce flight cancellations and delays for travelers.

While an aircraft may be capable of safe flight in some weather conditions, it is important for service providers and their personnel to understand how safe but frightening weather conditions can affect passenger comfort and willingness to fly. Just because an aircraft is capable of safely operating in some adverse conditions, it may still contribute to passenger aversion or discomfort due to factors such as noise, vibrations, and bumpiness. Education and outreach on aircraft capabilities and the types of weather conditions that could be hazardous may be able to help mitigate some of these concerns.

More research is needed to study the opportunities and risks weather poses to UAM operations and community perception across a greater sample of cities. Additionally, more research is needed to understand willingness to fly in a variety of weather conditions using actual UAM aircraft.

Given the interconnected nature of surface transportation providing first- and last- mile connections to UAM flights, all connected and automated transportation infrastructure, vehicles, and aircraft should collect and share meteorological data to improve safety and transportation systems management. Looking forward, the ability to accurately forecast UAM weather and provide a dependable consumer experience will be a key enabler for the UAM sector. Improved weather monitoring, big data, and predicative weather analytics present opportunities for UAM service providers to manage demand, reduce delays, and enhance the traveler experience.

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