Title

An Assessment of the Potential Weather Barriers of Urban Air Mobility (UAM)

Authors

Reiche, Colleen, PhD
Brody, Frank
McGillen, Christian
et al.

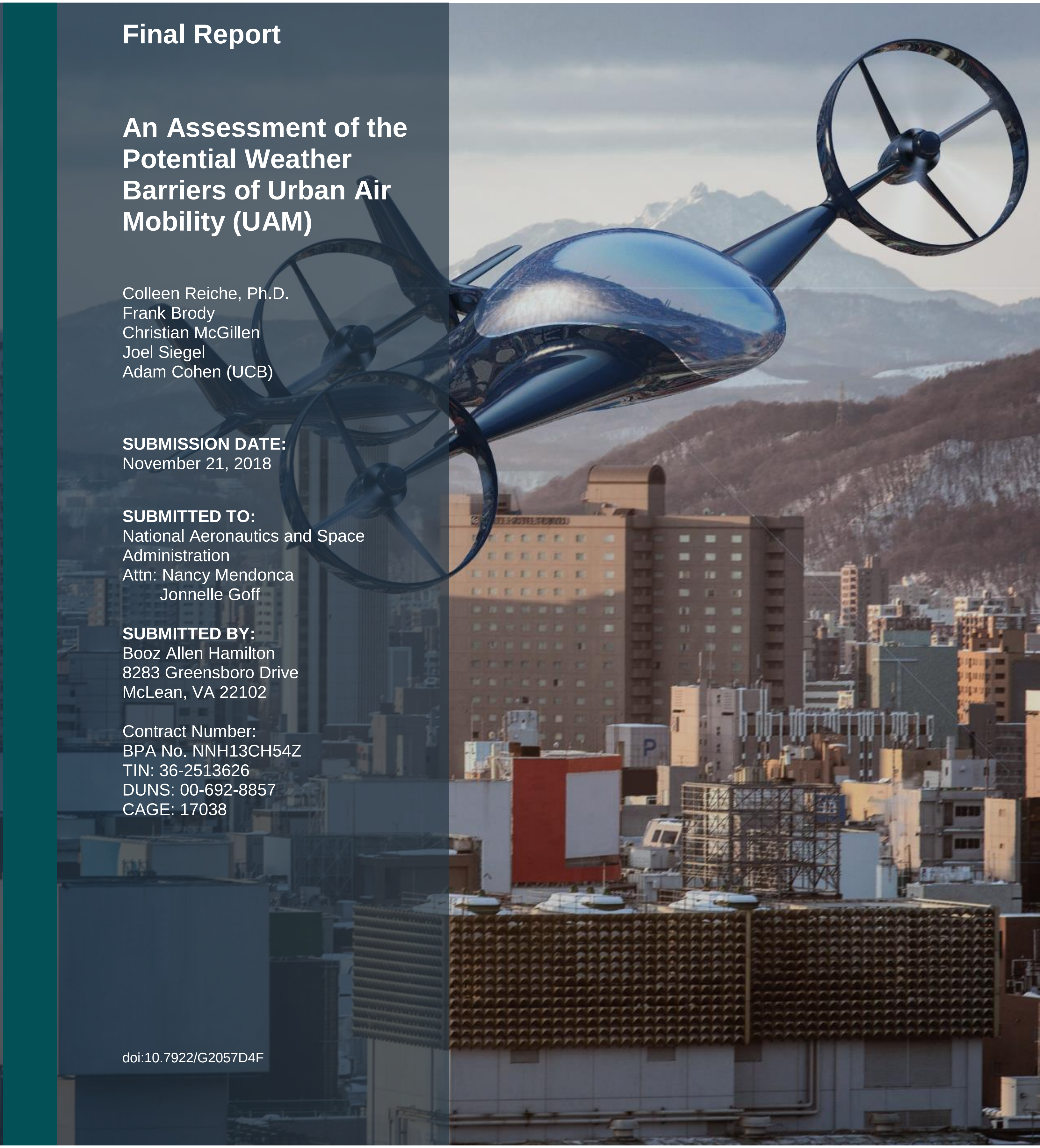
Publication Date

2018-11-21

DOI

10.7922/G2057D4F

Booz | Allen | Hamilton



Final Report

An Assessment of the Potential Weather Barriers of Urban Air Mobility (UAM)

Colleen Reiche, Ph.D.
Frank Brody
Christian McGillen
Joel Siegel
Adam Cohen (UCB)

SUBMISSION DATE:
November 21, 2018

SUBMITTED TO:
National Aeronautics and Space Administration
Attn: Nancy Mendonca
Jonnelle Goff

SUBMITTED BY:

Booz Allen Hamilton
8283 Greensboro Drive
McLean, VA 22102

Contract Number:
BPA No. NNH13CH54Z
TIN: 36-2513626
DUNS: 00-692-8857
CAGE: 17038

doi:10.7922/G2057D4F

TABLE OF CONTENTS

1.0 INTRODUCTION 4
2.0 WEATHER BARRIERS 4
2.1 Methodology 4
2.1.1 Weather Data Sources 4
2.1.2 Historical Statistics 5
2.1.3 Impacted Hours 6
2.2 Results 8
2.2.1 Western Urban Areas 8
2.2.2 Eastern Urban Areas 9
2.2.3 Texas Urban Areas 10
2.2.4 Density Altitude 10
2.2.5 Weather Impacted Hours 11
3.0 SUMMARY AND KEY FINDINGS 12
4.0 APPENDIX 14

LIST OF FIGURES

Figure 1: Surface and vertical sounding observation locations for 6 of the 10 target urban areas. Color shading area indicates spatial coverage of urban areas according to the U.S. Census 5
Figure 2: Distribution of PIREPs by weather condition at focus urban areas. No PIREPs were generated across our historical period in Honolulu 6
Figure 3: Average impact scores for each hour of UAM operational day at San Francisco urban area in summer 8
Figure 4. Time series of frequency of winds above 20 kts by season in Honolulu urban area. 8
Figure 5: Hourly summer frequency of winds above 20 kts at SFO (orange) and OAK (green) 9
Figure 6: Time series of median temperature in summer (top left), frequency of thunderstorms by season (top right), and frequency of winds above 20 kts by season (bottom left) in Phoenix urban area. 14
Figure 7: Hourly summer frequency of IFR conditions at LAX (orange) and VNY (blue) in Los Angles urban area 14
Figure 8: Time series of frequency of winds above 20 kts in summer at OAK and SFO (top left), station aggregate by season (top right), and frequency of IFRfrequency of non-VFR conditions in summer (bottom left) in San Francisco urban area. 15
Figure 9: Time series of frequency of non-VFR conditions in summer at LAX and VNY (left) and in aggregate by season in Los Angeles urban area. 15
Figure 10: Time series of frequency of thunderstorms by season (top left), frequency of non-VFR conditions by season (top right), and 5th percentile (blue line), median (purple line), and 95th percentile (red line) temperature by season (bottom) in Denver urban area. 16
Figure 11: Spatial distribution of PIREPs (left) and percentage of total reports by reported condition across historical period in Denver urban area. 16
Figure 12: Time series of frequency of thunderstorms in summer (left) and frequency of non-VFR conditions in summer (right) in Washington, D.C. urban area. 17
Figure 13: Spatial distribution of PIREPs (left) and percentage of total reports by reported condition across historical period in Washington, D.C. urban area. 17
Figure 14: Time series of frequency of winds above 20 kts in winter by METAR location (top left), frequency of non-VFR conditions by season (top right), and vertical distribution of wind speed during winter morning in New York urban area. 18
Figure 15: Spatial distribution of PIREPs (left) and percentage of total reports by reported condition across historical period in New York urban area. 18
Figure 16: Time series of frequency of non-VFR conditions by season (left) and frequency of thunderstorms by season (right) in Miami urban area. 19
Figure 17: Time series of frequency of non-VFR conditions in winter at HOU and IAH (top left), frequency of thunderstorms by season (bottom left), frequency of non-VFR conditions in aggregate by season (bottom right), and temperature statistics by season in Houston urban area. 19
Figure 18: Spatial distribution of PIREPs (left) and percentage of total reports by reported condition across historical period in Houston urban area. 20
Figure 19: Time series of frequency of non-VFR conditions by season (top left), frequency of thunderstorms by season (top right), median temperature in summer (bottom left), and vertical distribution of wind speed during fall at both 12Z and 00Z in Dallas urban area. 20

LIST OF TABLES

Table 1: Impact Scores for each weather condition from METAR 7
Table 2: Average seasonal density altitude for focus urban areas. 10
Table 3: Average number of weather impacted hours for all target urban areas by season........ 11

1.0 INTRODUCTION

Urban Air Mobility (UAM) is an emerging concept of air transportation where small package delivery drones to passenger-carrying air taxis operate over populated areas from small towns to the largest cities. This could revolutionize the way people move within and around cities by shortening commute times, bypassing ground congestion, and enabling point-to-point flights across cities. In recent years, several companies have designed and tested enabling elements of this concept, including; prototypes of Vertical Take-Off Landing (VTOL) capable vehicles, understanding of operational concepts, and development of potential business models. While UAM may be enabled by the convergence of several factors, several challenges could prevent its mainstreaming, such as weather.

2.0 WEATHER BARRIERS

Weather constraints represent a critical and complex component of characterizing the UAM market. Weather can influence many components of UAM, including operations, service supply, passenger comfort, community acceptance, infrastructure, and traffic management. In this study, our goal was to provide an initial assessment of underlying historical weather conditions, or a climatology, which could impact UAM, with a focus on operations. No assumptions were made regarding vehicles or technology, so results could be made more precise by examining specific use cases in the future.

2.1 Methodology

This section will describe our weather analysis methodology used to develop the climatology, including data sources, generation of climatology at the ten focus urban areas, and consolidation of results into overall weather impacted hours.

2.1.1 Weather Data Sources

We first surveyed available data sources in and near focus urban areas, and found limited availability of high resolution, reliable (calibrated) observations collected directly in the urban areas. We therefore targeted regularly collected weather observations including Meteorological Aerodrome Report (METAR), vertical soundings, and pilot reports (PIREP) for our 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. PIREPs are generated whenever a pilot encounters weather conditions that they deem impactful, such as low-level wind shear or turbulence. These are not collected at a regular time interval, so they are used in this analysis as a supplemental source of weather impacts to augment signals observed from the METAR and vertical soundings.

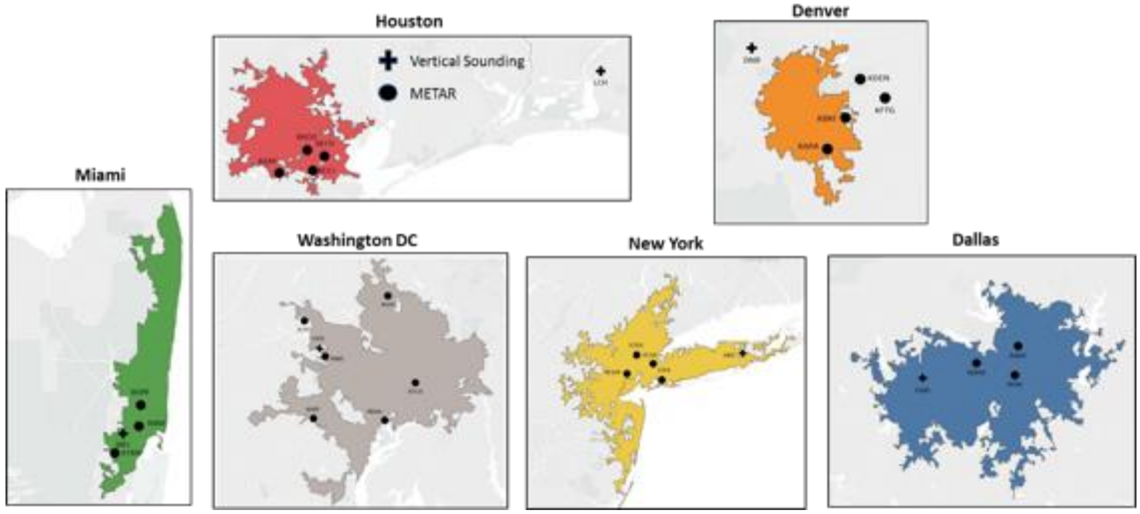


Figure 1: Surface and vertical sounding observation locations for 6 of the 10 target urban areas. Color shading area indicates spatial coverage of urban areas according to the U.S. Census

We evaluated the spatial extent and distribution of observation locations relative to the focus urban areas 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 urban areas but may not be fully representative of conditions in many. In most of the Eastern 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 (Figure 1). 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. Despite these limitations, these observations provide a valuable baseline on historical adverse conditions in the target urban areas from which weather barriers to UAM can be assessed.

2.1.2 Historical Statistics

Weather conditions potentially impactful to UAM operations can vary strongly both diurnally and seasonally in many of our target urban areas, so we stratified our 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). We focused our analysis on the anticipated UAM operational window of 7 am – 6 pm Local Time to align with our economic market analysis, but have data for all 24 hours of the day.

For METAR surface observations, we computed statistics over a 7-year historical period (2010-2017) such as average temperature and frequency of conditions such as thunderstorms and Instrument Flight Rules (IFR) for each hour of the UAM 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. For example, we found a significant difference in the frequency of winds greater than 20 kts in the San Francisco urban area during summer in the afternoon, with frequency greater than 50% at SFO (west of the Bay) but under 5% at OAK (east of the Bay) around 4 pm Local Time. This indicates that during this time and season, wind conditions are much more favorable for UAM operations in the eastern urban area than the western portion. We then calculated these statistics across all METAR stations in aggregate to analyze the seasonal variability in conditions across the urban area. Continuing the San Francisco example, we found that in aggregate, the frequency of winds greater than 20 kts is greatest (~20%) during afternoon in most seasons but only about 10% during winter indicating that across the urban area, wind conditions are slightly more favorable for UAM operations in winter.

As indicated earlier, the vertical sounding observations are only collected twice a day, so we 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 we calculated average conditions in 500 ft bins 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.

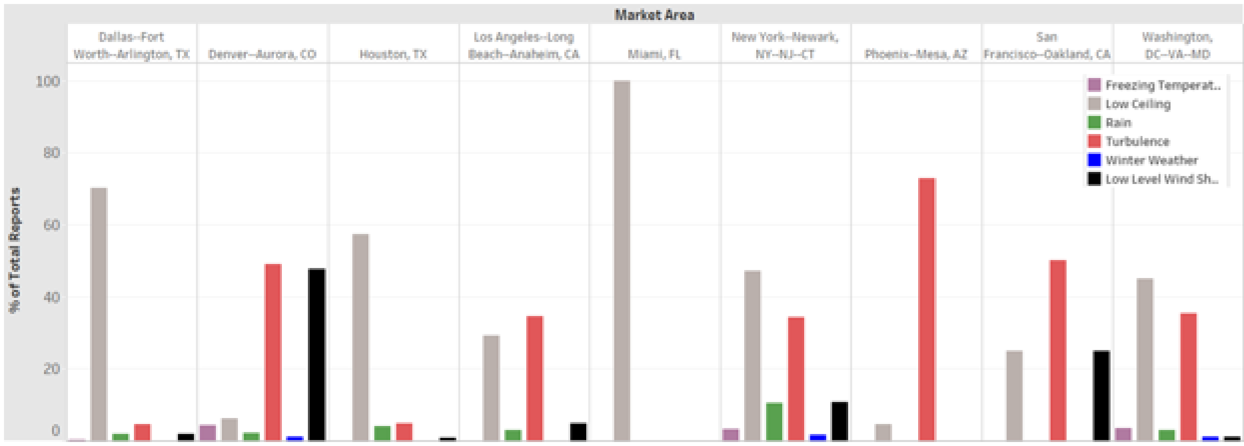


Figure 2: Distribution of PIREPs by weather condition at focus urban areas. No PIREPs were generated across our historical period in Honolulu

Pilot reports were used as supplemental observations to augment results from the surface and vertical sounding observations due to their ad hoc collection. We first isolated PIREPs across a 3-year historical period (2015-2017) over or near the focus urban areas using the airport code in the reports. Within each urban area, we then computed the percentage of reports with each type of reported weather to identify which conditions were most prevalent (Figure 2). 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 including Denver and San Francisco. Because more than one condition may be included in a given report, these percentages may not always add up to 100%.

2.1.3 Impacted Hours

After generating detailed statistics on historical weather conditions individually, we computed the overall average number of hours that UAM operations could potentially be significantly impacted based on the underlying conditions. The goal of capturing these 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 based on METAR surface observations as they provide the highest temporal resolution (hourly) of all our data sources.

To do this, we first 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). We leveraged our extensive expertise in aviation weather as well as available literature on weather influence on UAS and UAM vehicles to define these scores which are shown in (Table 1). These scores are preliminary and were defined to capture potential impacts across a wide range of UAM operations and make no assumptions about components such as vehicle type or level of automation. Further refinement and precision of the weather impact scores could be achieved through case studies where these components are explicitly defined. Vertical wind shear is a critical 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.

Table 1: 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		IFR 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
IFR 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			

We then computed the average impact score at each hour of the UAM operational day for each season at all target urban areas, based on conditions that occurred historically during that hour. To define an hour of the UAM operational day as “impacted”, we needed to define an average impact score threshold. We evaluated variability of the average impact score distributions, as well as the impact scores themselves, and determined that an average impact score threshold of 3 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., vehicle type). Therefore, if the average impact score for any hour of any season exceeded 3, we considered that hour to be potentially impacted by weather, or an “impacted hour”. The number of impacted hours was summed across the UAM operational day for each season. For example, the average impact score during summer at San Francisco exceeded 3 from 1-6 pm Local Time, leading to a total of 6 weather impacted hours (Figure 3).

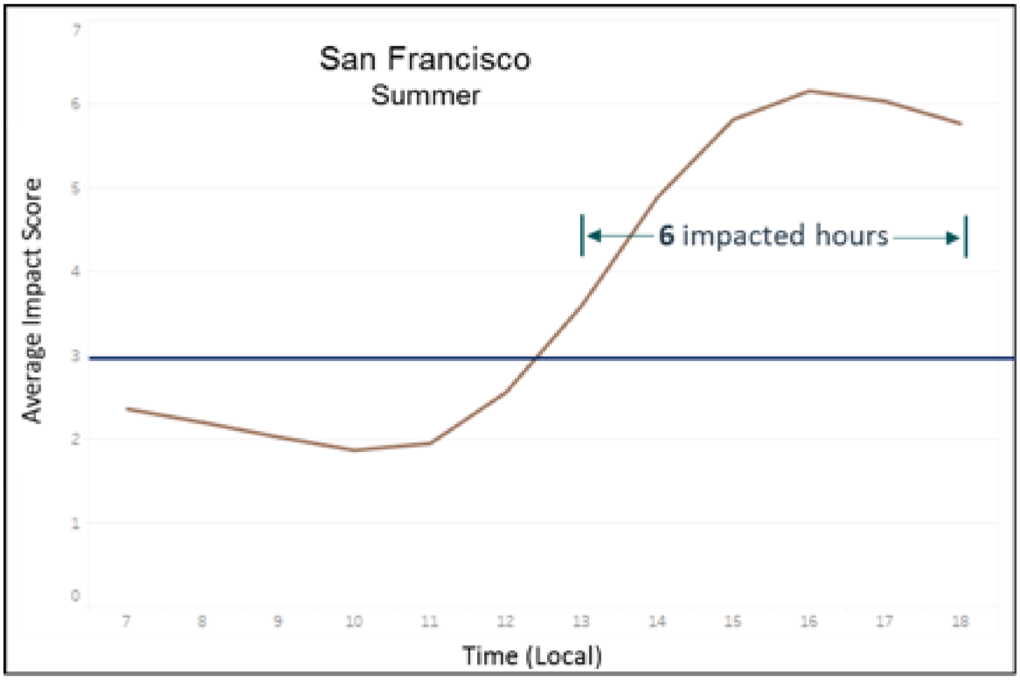


Figure 3: Average impact scores for each hour of UAM operational day at San Francisco urban area in summer

2.2 Results

This section will describe our results, focusing on key signals including high historical frequency of potentially impactful weather conditions, variability in conditions within an urban area as well as diurnally and seasonally, and average number of impacted hours. Because the sample size of historical PIREPs was not sufficient to evaluate seasonal or diurnal variability in conditions, we evaluated the spatial distribution of reported conditions in each urban area to augment signals observed from surface and vertical soundings. Results will be presented for urban area regions first, followed by density altitude across all urban areas, and lastly impacted hours. Supplemental figures to augment results presented here can be found in (4.0 AppendixA).

2.2.1 Western Urban Areas

Overall, weather conditions are favorable for UAM operations at most western focus urban areas. 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 (Figure 4). Phoenix experiences several weather conditions on average that may be impactful to UAM, including high temperatures, strong winds, and thunderstorms (Figure 6 in Appendix). These unfavorable conditions occur most frequently during afternoon in summer. Most pilot reports in Phoenix were due to turbulence and were uniformly distributed spatially across the urban area. In the Los Angeles urban area, weather conditions are mostly favorable for UAM operations,

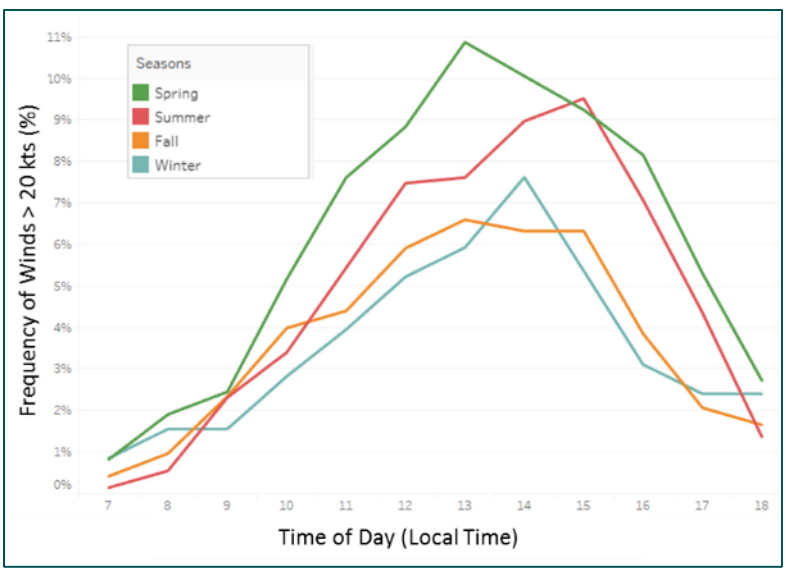


Figure 4. Time series of frequency of winds above 20 kts by season in Honolulu urban area.

though IFR conditions are somewhat frequent in morning, especially during summer. There was also variability within urban area during summer, where historical IFR frequency was above 50% in early morning at LAX while only about 20% at Van Nuys (Figure 7 in Appendix). Most PIREPs were due to turbulence, located mostly over the ocean, and low ceilings, located mostly in the western urban area which is consistent with findings from METAR observations.

We also found variability in conditions within the San Francisco urban area, which frequently experiences IFR and winds above 20 kts in most seasons (Figure 8 in Appendix). The frequency of winds above 20 kts is significantly greater at SFO than OAK in all seasons except for winter (Figure 5). This suggests that wind conditions are more favorable for UAM in the eastern portion of the urban area during afternoon hours. IFR conditions also have a high historical frequency during morning hours, exceeding 60% before 8 am Local Time in summer. Similarly, Figure 9 in the Appendix shows the frequency of non-VFR conditions for the Los Angeles urban area with Van Nuys, being further inland, having lower frequency of non-VFR hours than LAX which is nearer the coast.

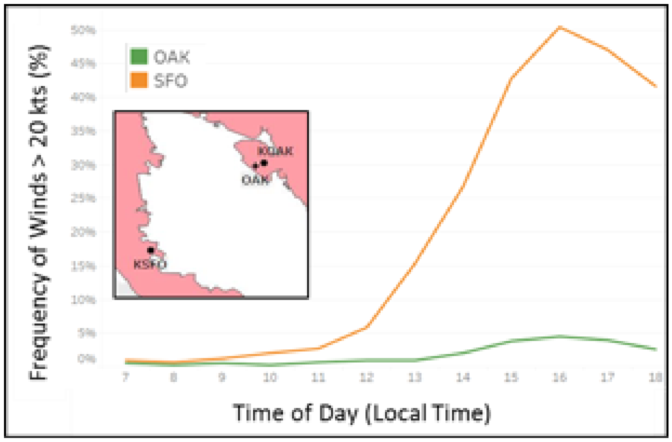


Figure 5: Hourly summer frequency of winds above 20 kts at SFO (orange) and OAK (green)

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 vehicle battery life are possible during fall, winter, and spring especially in the morning hours. IFR 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 (Figure 10Figure 11: Spatial distribution of PIREPs (left) and percentage of total reports by reported condition across historical period in Denver urban area. in Appendix). 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 (Figure 11: Spatial distribution of PIREPs (left) and percentage of total reports by reported condition across historical period in Denver urban area.Figure 11 in Appendix). Turbulence and wind shear were the most frequently reported conditions and were distributed uniformly across the urban area spatially.

2.2.2 Eastern Urban Areas

Average weather conditions were found to be less favorable in the Eastern focus urban areas than the Western areas. In Washington, D.C., thunderstorms and IFR conditions are the most frequent potentially impactful weather. IFR conditions are on average most common in the early morning during all seasons while thunderstorms occurred most often in afternoon during summer (Figure 12 in Appendix). Most PIREPs were due to turbulence and low ceilings, the majority of which were reported while departing out of IAD in the western portion of the urban area (Figure 13 in Appendix).

Several adverse conditions were frequent in the New York urban area for most hours and seasons, which included IFR, winds above 20 kts, and rapid changes in wind speed with altitude, or vertical wind shear (Figure 14 in Appendix). Variability in strong winds was observed within the urban area, with JFK (on Long Island in eastern portion of the urban area) experiencing the highest frequency of winds above 20 kts during afternoon (~14%) while a significantly lower frequency of occurrence (~2%) was observed at TEB (northern portion of urban area). Across the urban area in aggregate, IFR 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 UAM during takeoff and in flight. Similar to Washington, D.C., most PIREPs in the New York urban area indicated turbulence and low ceilings (Figure 15 in Appendix).

Overall, average weather conditions in the Miami urban area were favorable for UAM operations. Thunderstorms occurred frequently during early afternoon in summer and fall, while IFR conditions were somewhat common during winter in the early morning hours (Figure 16 in Appendix).

2.2.3 Texas Urban Areas

In the two Texas urban areas, frequent thunderstorms, IFR, and vertical wind shear conditions pose potential challenges for UAM operations in most seasons. In Houston, we found some variability in IFR condition frequency within the urban area (Figure 17 in Appendix). These conditions are most frequent during morning in winter and spring overall, but have a higher frequency at IAH (over 35%), in the northern part of the urban area, than at HOU (20%) which is in the southern portion of the urban area. A review of the PIREPS in the Houston urban area (Figure 18 in appendix) 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 safety of UAM operations. We also saw that a strong low-level jet, or altitude band with strong winds, was commonly present around 2500 ft in morning during winter along with strong winds near 5000 ft.

Average weather in the Dallas urban area was similar to Houston, with high temperature, IFR, thunderstorms, and strong low level jet being the most frequent potentially impactful conditions to UAM (Figure 19 in Appendix). 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. We also found that thunderstorms were more common during afternoon in spring than in Houston, possibly due to passage of strong cold fronts that are frequent during spring.

2.2.4 Density Altitude

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, is shown in Table 2 along with the field elevation from which the observations were taken. These values are 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), which may result in impacts to UAM takeoff and lift. Average density altitude is also about 1000-2000 ft above surface elevation in Miami during both summer and fall, and Dallas, Denver, and Houston during summer.

Table 2: Average seasonal density altitude for focus urban areas.

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

Honolulu	98	1039	1498	1248	885

2.2.5 Weather Impacted Hours

As described earlier, we computed the overall average number of weather impacted hours during the UAM operational day (7 am – 6 pm Local Time) for each season across all focus urban areas. These weather impacted hours are shown in Table 3, along with the average across all seasons in the rightmost column. According to 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 New York, Washington, D.C., Dallas, Houston, Denver, and Honolulu.

We found a high number of weather impacted hours, sometimes more than half of the UAM operational day, occurred during winter and spring in the Northeast, Texas, and Denver urban areas. Conversely, most urban areas experienced the fewest impacted hours during summer and fall with the exceptions being Honolulu and Phoenix. Due to the high frequency of several impactful conditions during summer in Phoenix, including thunderstorms and high temperatures, almost half of the operational day would potentially be influenced by adverse weather during summer. In Honolulu, the high frequency of strong winds through most of the operational day during summer results in nine weather impacted hours during summer.

Despite historical occurrence of adverse conditions like 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 our threshold of 3. These results would benefit from refinement of our impact scores to capture the fact that underlying frequency of occurrence is different for all phenomena, with smaller values expected for small scale, short-lived conditions like thunderstorms.

Table 3: Average number of weather impacted hours for all target urban areas by season

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

3.0 Summary and Key Findings

From the weather analysis, we found that synthesis of potential weather impacts across a broad range of operations and vehicles is a challenge. For example, IFR conditions could be highly impactful if assuming piloted VFR-only operations, but minimal for fully-automated vehicles equipped with sensors to enable IFR flight. The impact scores would likely vary depending on operation specifics. For a future study, we recommend exploring some specific case examples to apply detailed assumptions on vehicle and operations to more fully explore the range in weather impacts. This would also enable weather barriers to be more fully captured into the market analysis supply and demand models.

Key Findings	We found the following key results from the weather barriers analysis: • Weather most favorable for UAM operations in Western focus urban areas, which experience weather impacted hours for less than half of the operational window mostly due to frequent high temperatures and IFR conditions during summer and strong surface winds • Weather conditions highly unfavorable for UAM operations in Denver due to frequent adverse weather in all seasons • Approximately half of the UAM operational day potentially impacted by weather on average in Texas urban areas due to thunderstorms, IFR conditions, and vertical wind shear • Weather conditions less favorable in New York and Washington, D.C. focus urban areas as potential for most of operational day to be impacted by weather on average across all seasons primarily due to IFR conditions, strong surface winds, and vertical wind shear • Weather favorable for UAM operations in Miami, though thunderstorms could cause short term disruptions mostly in fall and summer

4.0 Appendix

The appendix provides more figures for the weather analysis.

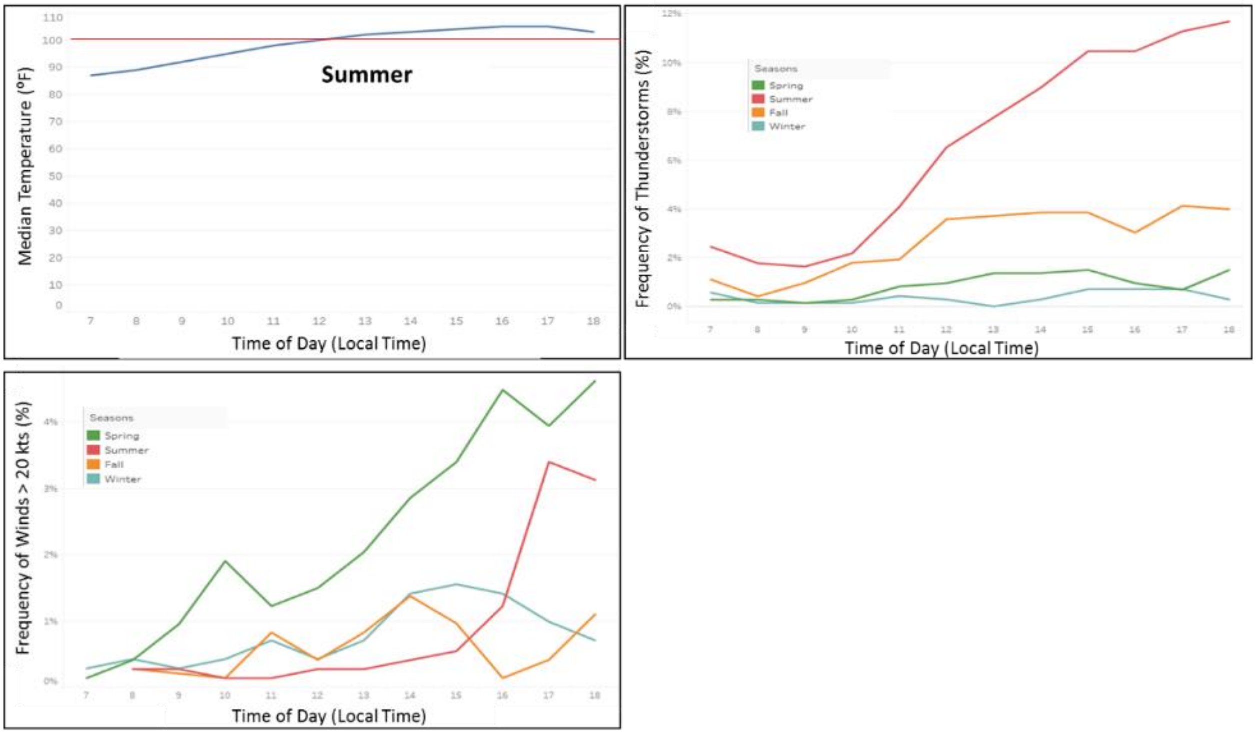


Figure 6: Time series of median temperature in summer (top left), frequency of thunderstorms by season (top right), and frequency of winds above 20 kts by season (bottom left) in Phoenix urban area.

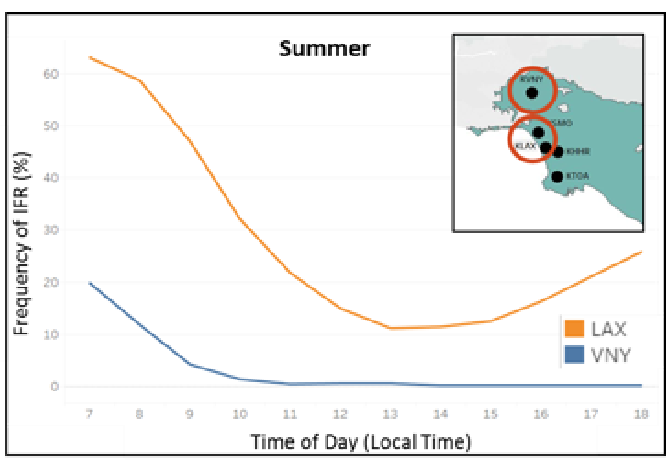


Figure 7: Hourly summer frequency of IFR conditions at LAX (orange) and VNY (blue) in Los Angles urban area

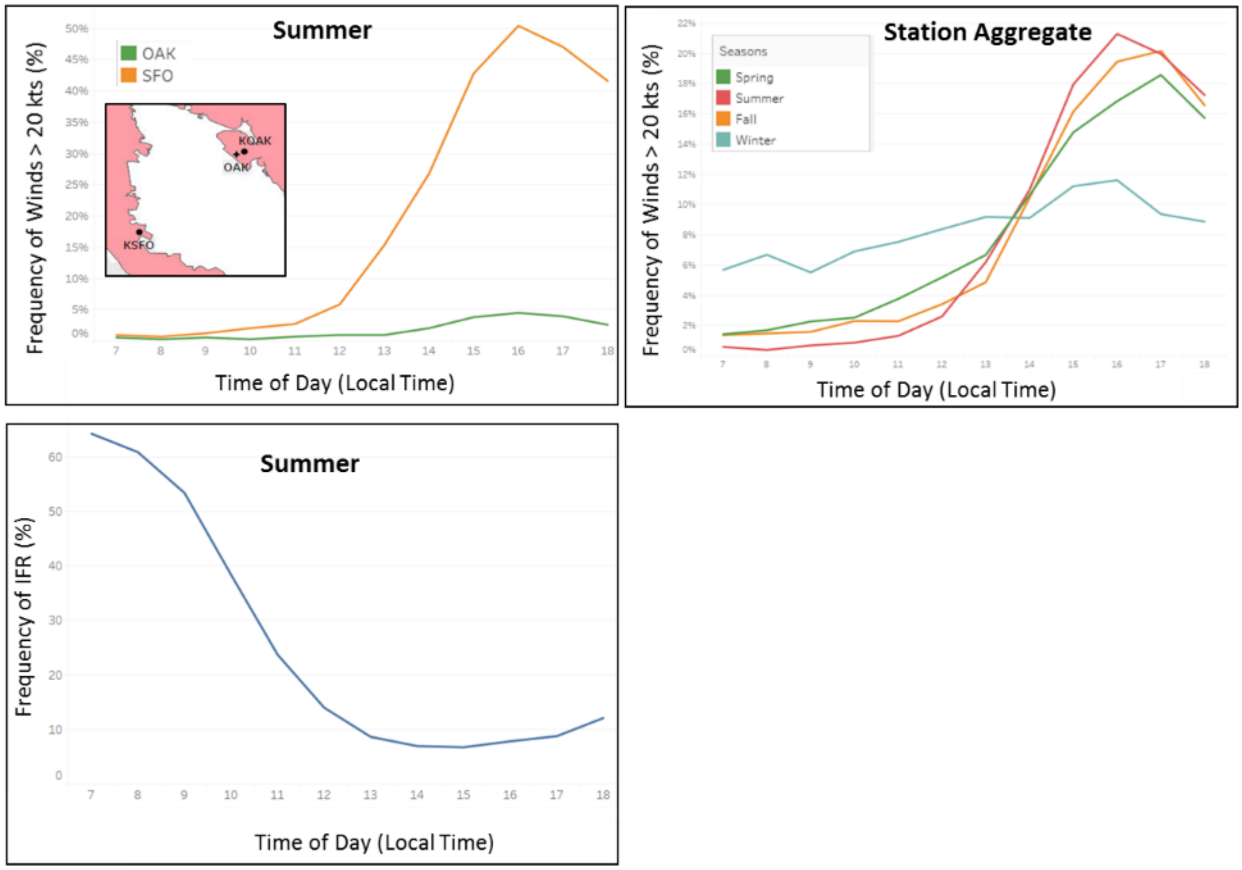


Figure 8: Time series of frequency of winds above 20 kts in summer at OAK and SFO (top left), station aggregate by season (top right), and frequency of IFRfrequency of non-VFR conditions in summer (bottom left) in San Francisco urban area.

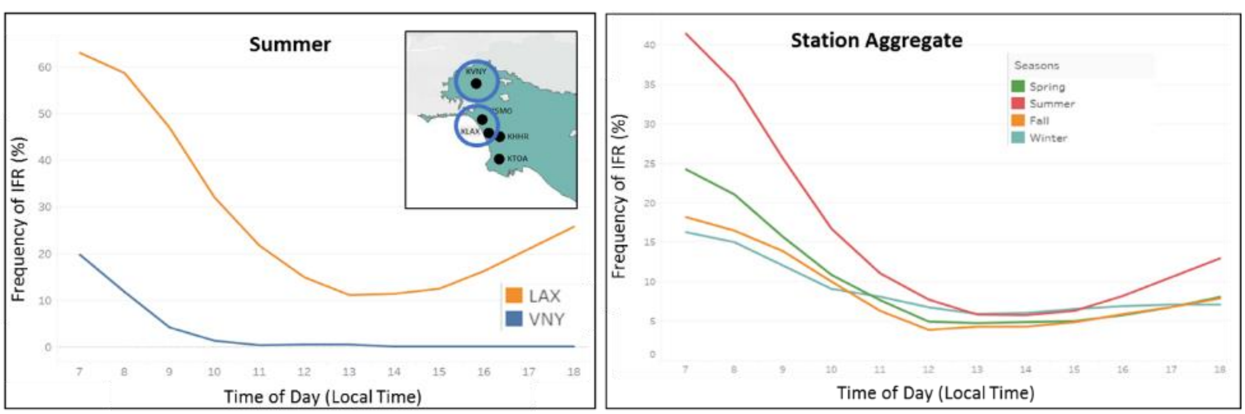


Figure 9: Time series of frequency of non-VFR conditions in summer at LAX and VNY (left) and in aggregate by season in Los Angeles urban area.

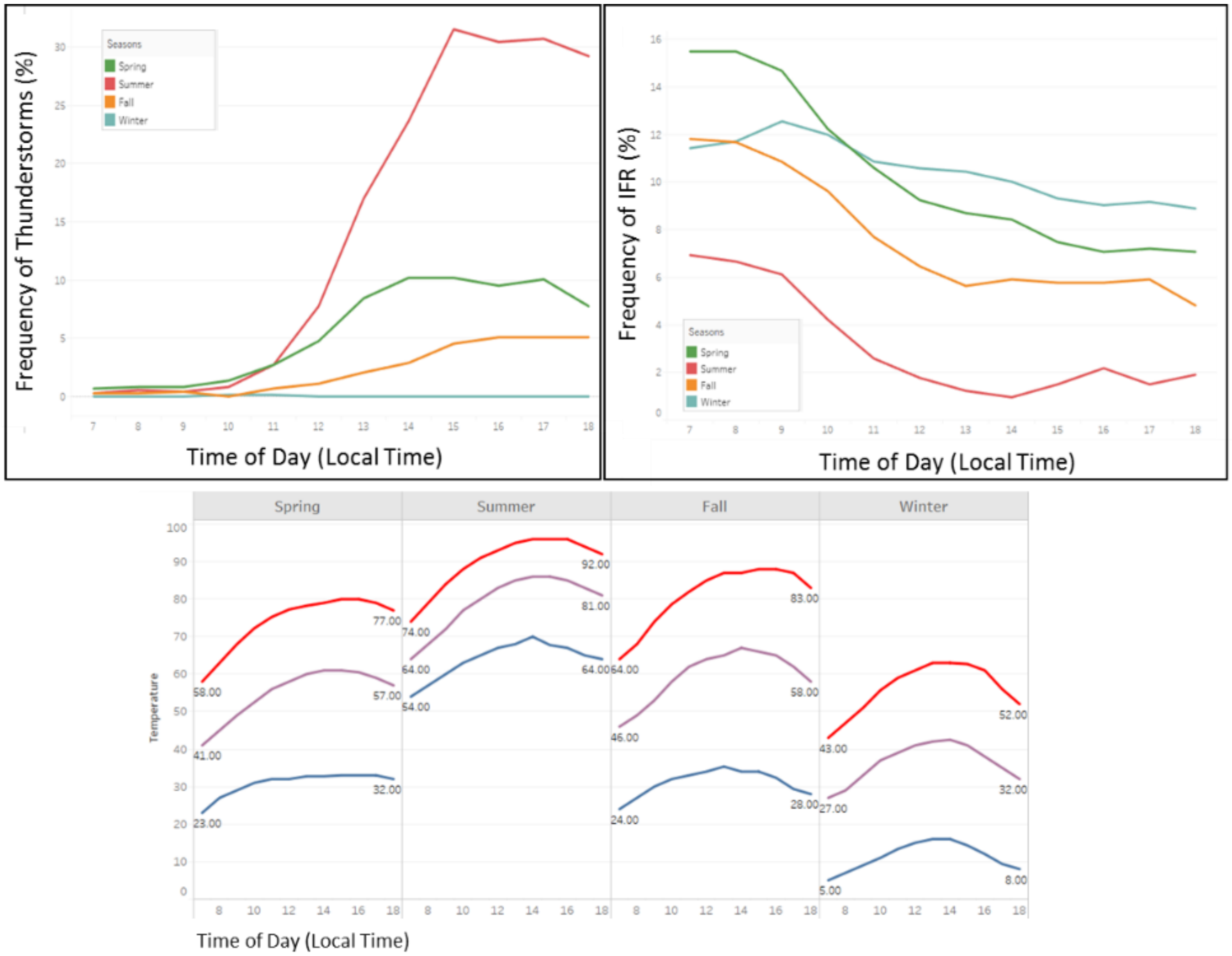


Figure 10: Time series of frequency of thunderstorms by season (top left), frequency of non-VFR conditions by season (top right), and 5th percentile (blue line), median (purple line), and 95th percentile (red line) temperature by season (bottom) in Denver urban area.

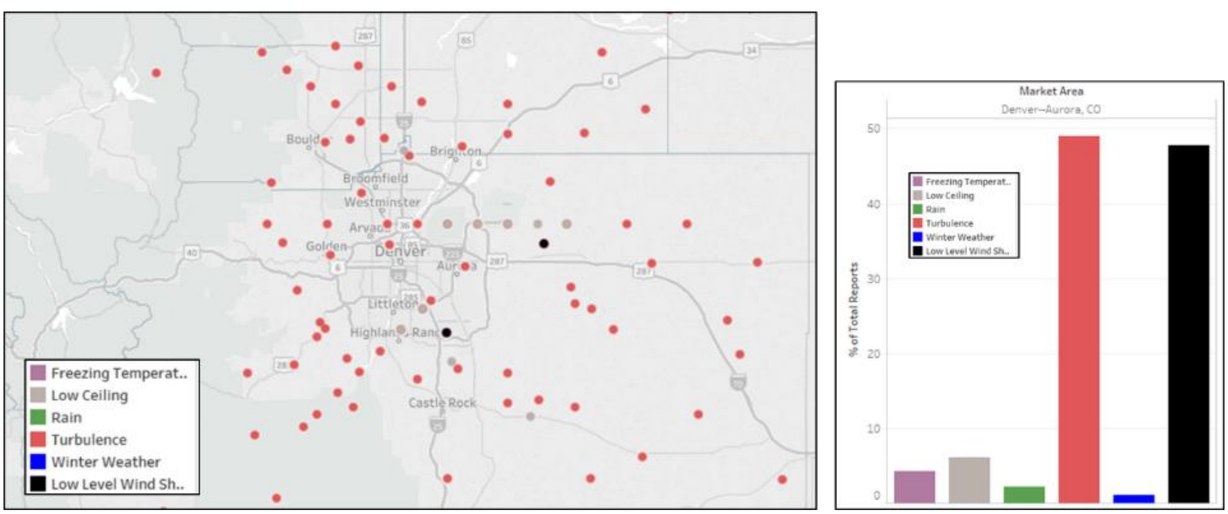


Figure 11: Spatial distribution of PIREPs (left) and percentage of total reports by reported condition across historical period in Denver urban area.

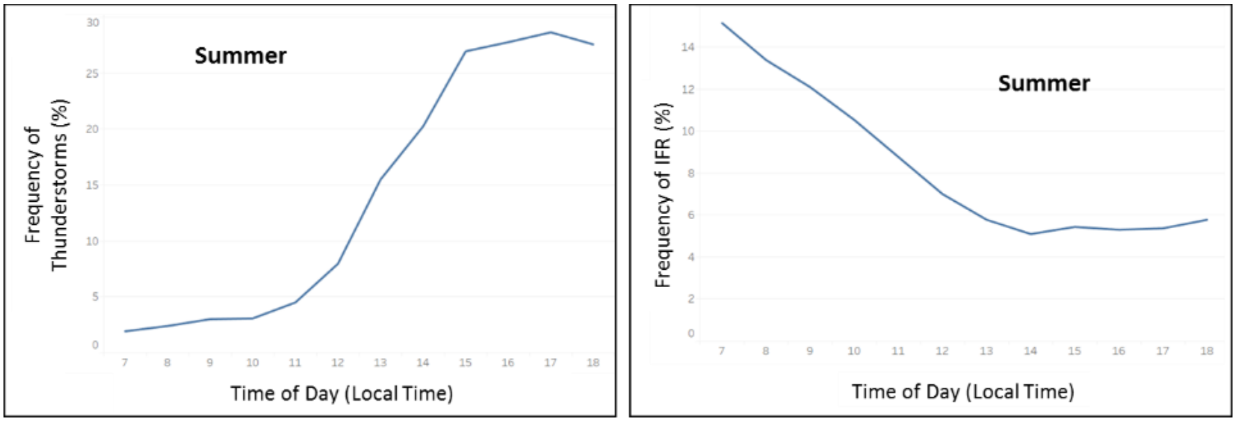


Figure 12: Time series of frequency of thunderstorms in summer (left) and frequency of non-VFR conditions in summer (right) in Washington, D.C. urban area.

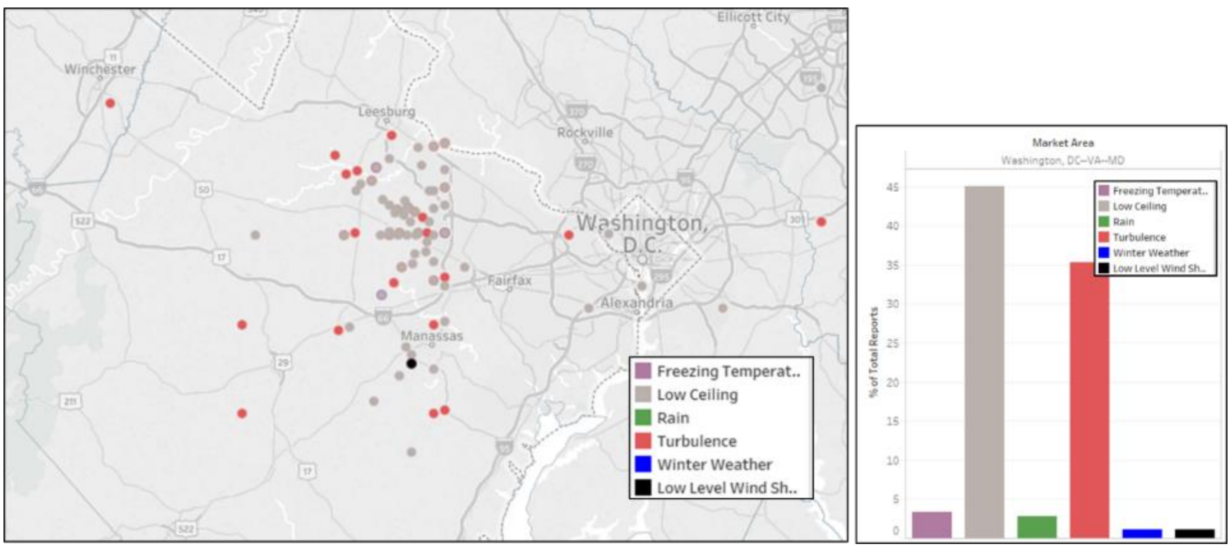


Figure 13: Spatial distribution of PIREPs (left) and percentage of total reports by reported condition across historical period in Washington, D.C. urban area.

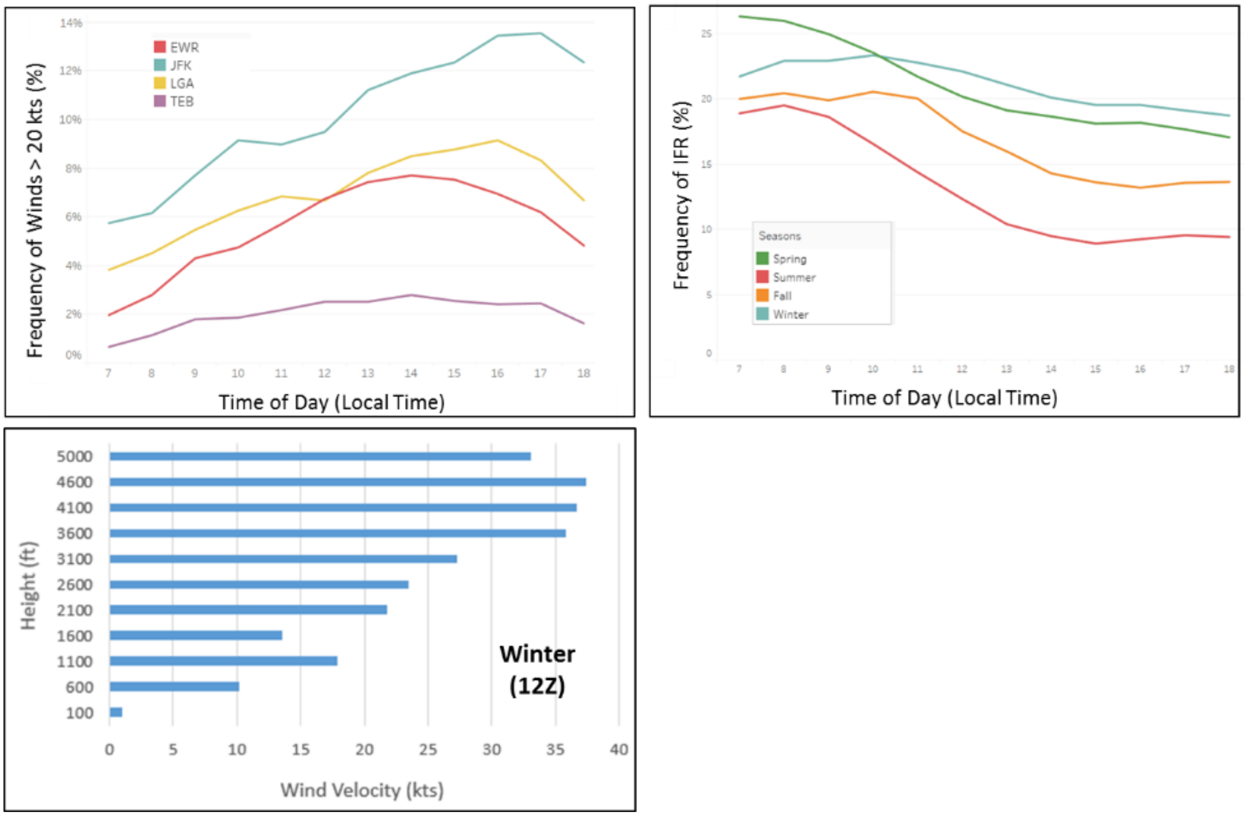


Figure 14: Time series of frequency of winds above 20 kts in winter by METAR location (top left), frequency of non-VFR conditions by season (top right), and vertical distribution of wind speed during winter morning in New York urban area.

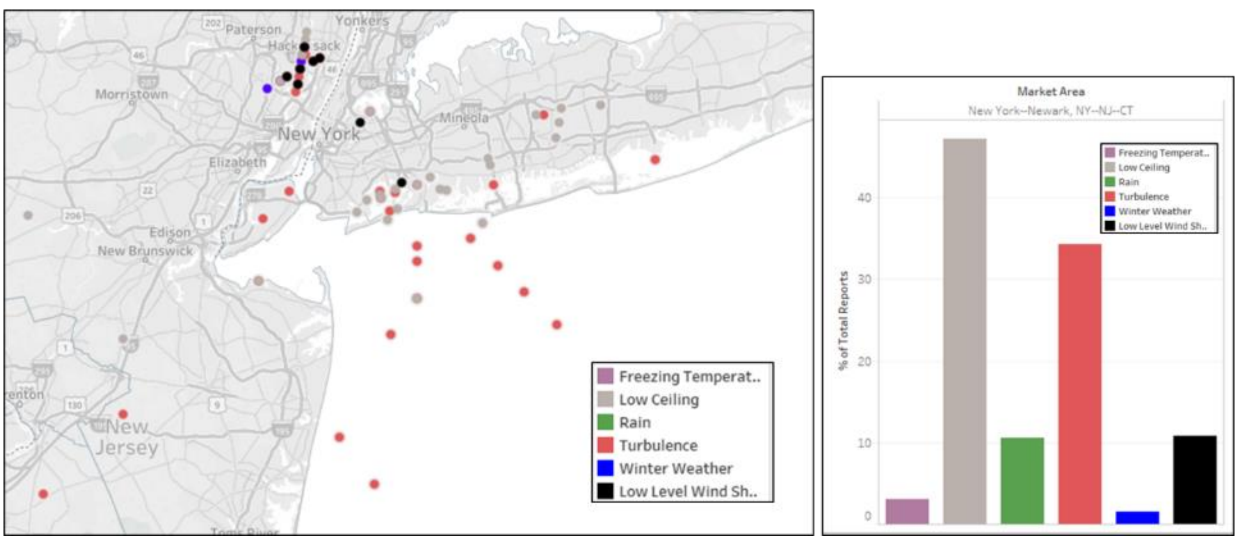


Figure 15: Spatial distribution of PIREPs (left) and percentage of total reports by reported condition across historical period in New York urban area.

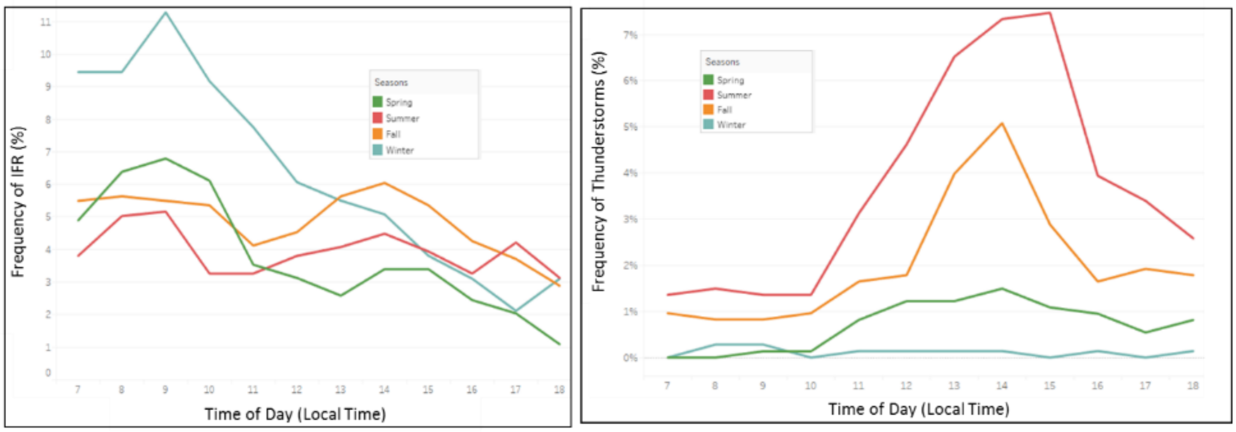
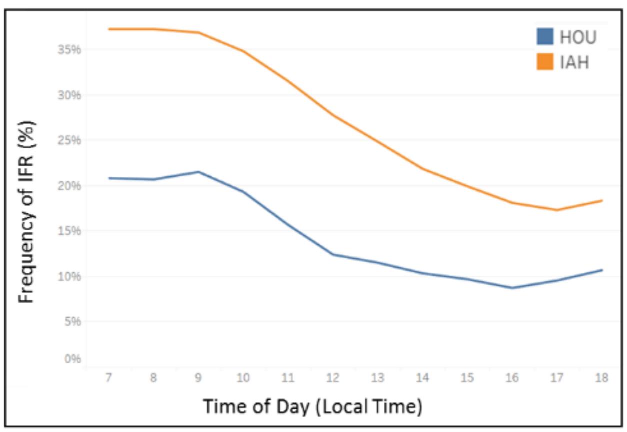


Figure 16: Time series of frequency of non-VFR conditions by season (left) and frequency of thunderstorms by season (right) in Miami urban area.



	Fall	Spring	Summer	Winter
TMax	99.00	97.00	105.00	86.00
TMin	32.00	28.00	70.00	23.00
Temp Range	67.00	69.00	35.00	63.00
Temp95P	90.00	86.00	96.00	77.00
Temp50P	78.00	75.00	88.00	60.00
Temp5P	54.00	56.00	77.00	39.00

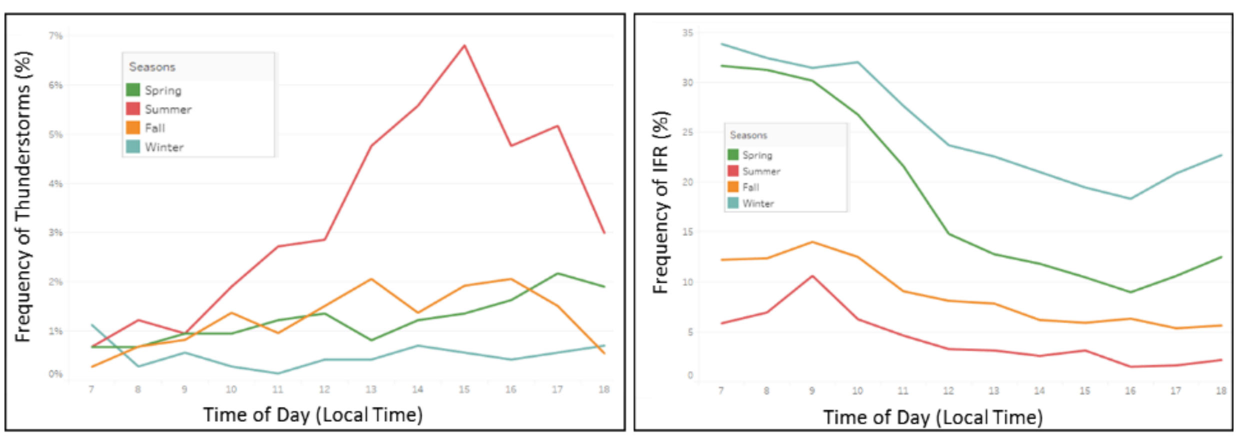


Figure 17: Time series of frequency of non-VFR conditions in winter at HOU and IAH (top left), frequency of thunderstorms by season (bottom left), frequency of non-VFR conditions in aggregate by season (bottom right), and temperature statistics by season in Houston urban area.

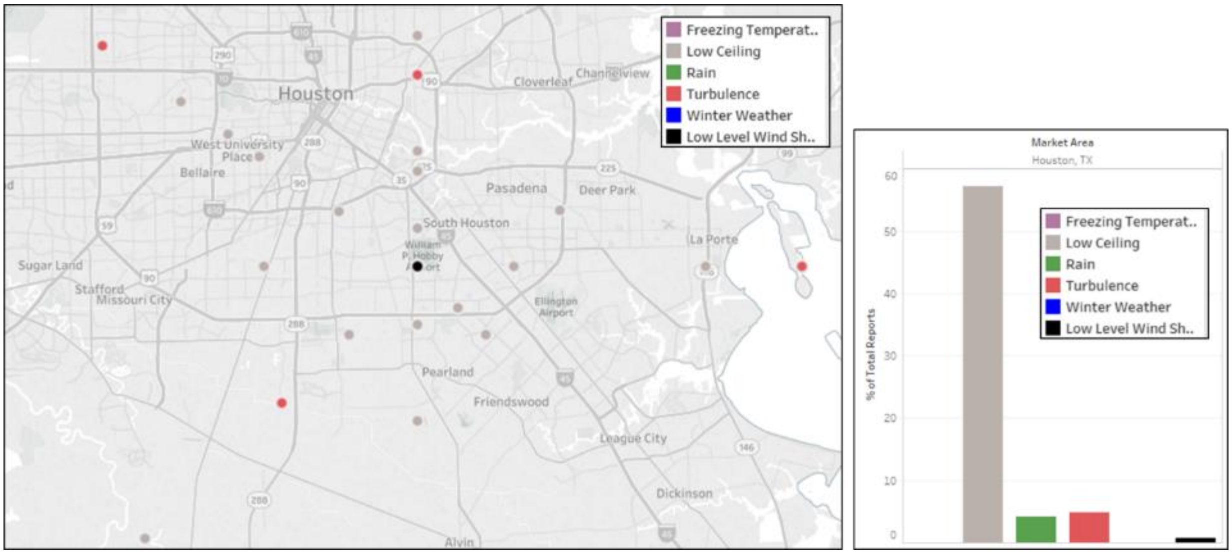


Figure 18: Spatial distribution of PIREPs (left) and percentage of total reports by reported condition across historical period in Houston urban area.

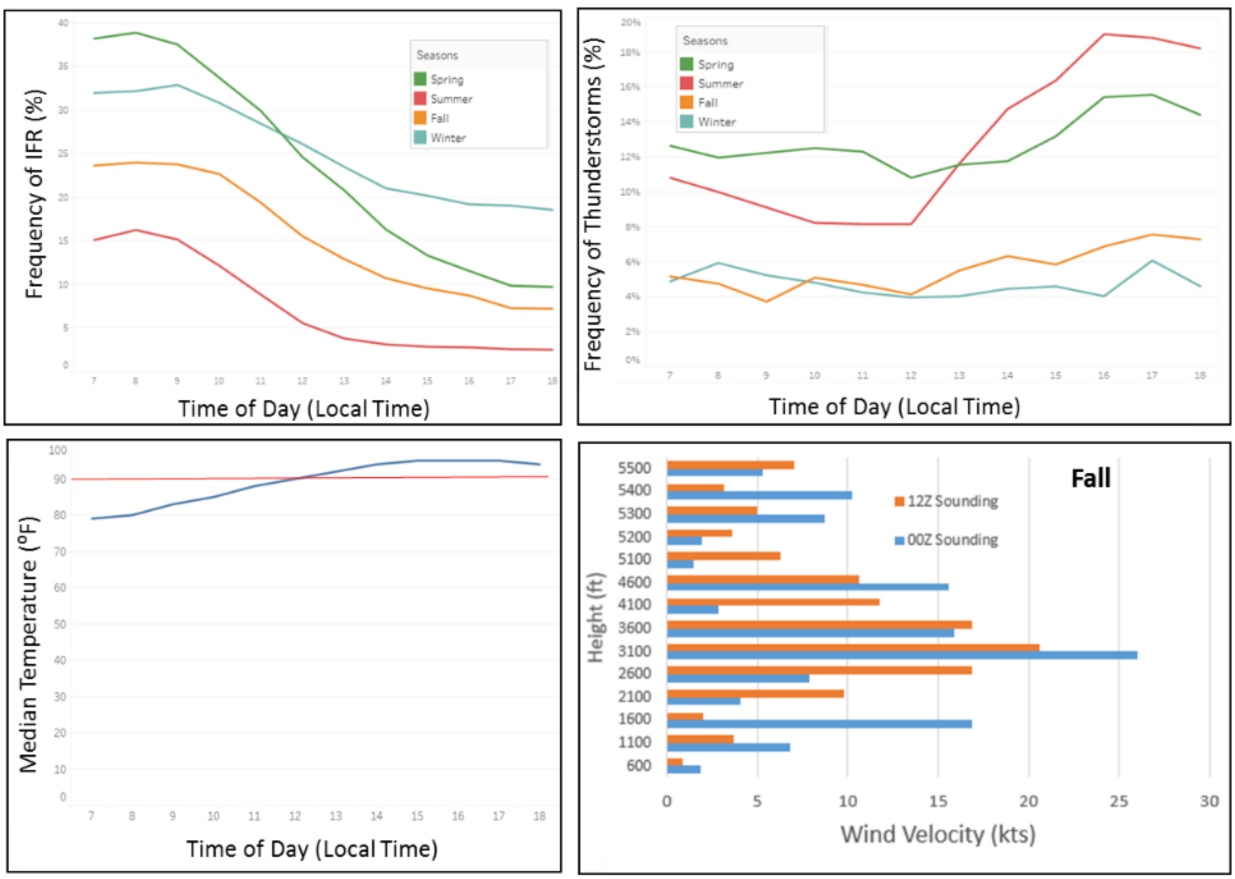


Figure 19: Time series of frequency of non-VFR conditions by season (top left), frequency of thunderstorms by season (top right), median temperature in summer (bottom left), and vertical distribution of wind speed during fall at both 12Z and 00Z in Dallas urban area.