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ASSESSMENT OF OBSERVED WEATHER IMPACTS ON SMALL UNMANNED AIRCRAFT (UA) OPERATIONS

by

Nicole Stevens
Bachelor of Science, University of North Dakota, 2017

A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

in partial fulfillment of the requirements

for the degree of

Master of Science

Grand Forks, North Dakota
December
2019

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This thesis, submitted by Nicole Stevens in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

Dr. Mark Askelson

Dr. Gretchen Mullendore

Michael Poellot

This thesis is being submitted by the appointed advisory committee as having met all of the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

Chris Nelson - Associate Dean
School of Graduate Studies

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Nicole Stevens
December 19, 2019

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LIST OF ACRONYMS

Acronym	Meaning
AGL	Above Ground Level
ASSURE	Alliance for System Safety of UAS through Research Excellence
ASOS	Automated Surface Observing System
AWOS	Automated Weather Observing System
C2	Command and Control
CONUS	Contiguous United States
CFR	Code of Federal Regulations
DAA	Detect and Avoid
ERAST	Environmental Research Aircraft and Sensor Technology
FAA	Federal Aviation Administration
FMH3	Federal Meteorological Handbook No. 3
GPS	Global Positioning System
IGRA	Integrated Global Radiosonde Archive
ISD	Integrated Surface Database
LOC	Loss of Aircraft Control
METAR	Meteorological Terminal Aviation Routine Weather Report
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NCEI	National Centers for Environmental Information
NTSB	National Transportation Safety Board
NWS	National Weather Service
Part 107	UAS Flown by Certified Remote Pilots including Commercial Operators
PIC	Pilot in Command
PIREPs	Pilot Weather Reports
QC	Quality Control
RTCA	Radio Technical Commission for Aeronautics
SAO	Surface Airway Observations
TFR	Temporary Flight Restriction
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
VLOS	Visual Line of Sight
VFR	Visual Flight Rule

ACKNOWLEDGMENTS

I cannot express enough thanks to my advisor, Dr. Mark Askelson, for his guidance and excitment in regards to teaching, sharing his passion and knowledge of unmanned aircraft, and the continued support he has provided throughout my graduate career. I would also like to thank my committee members, Dr. Gretchen Mullendore and Mike Poellot, for all of their constructive feedback, project review, and patience.

I also want to thank my family for encouraging me in all of my pursuits and inspiring me to follow my dreams. A special thank you to Dr. Mariusz Starzec for his endless support and assistance with project development. Thanks also to my friends and classmates for offering their advice and making everyday more fun.

I dedicate this thesis to my parents, Jay and Elaine Stevens, and my sister, Samantha. Thank you for the love, guidance, and support that you have given me, helping me to succeed and instilling in me the confidence that I am capable of doing anything I put my mind to.

ABSTRACT

Unmanned Aircraft (UA) are being used more frequently and for an increased variety of purposes, from military use to medical deliveries, disaster and building infrastructure imagery, and agriculture. While the interest and usage of UA grows, little is known about how often UA flight operations are impacted by different meteorological phenomenon. In this study, a 30-year climatology of surface stations and sounding observations are used to determine the likelihood of UA operations without weather-driven restrictions or grounding at five locations. The locations of Bismarck, ND, Riverton, WY, Oakland, CA, Albuquerque, NM, and Miami, FL are selected to represent different atmospheric and regional characteristics. Impacts from temperature, moisture, winds, and cloud base height are analyzed to determine the frequency with which thresholds, set utilizing previous studies on manned aircraft and testing of UA, are reached. Analysis of the surface data indicate that flight impacts vary by geographic location, season, and time of day. Temperature impacts primarily follow seasonal changes, whereas restrictions due to relative humidity and winds primarily follow diurnal variations. Analysis of sounding data produced similar restrictions overall, with impacts from relative humidity and winds changing with height. Data from soundings at the surface are consistent with surface data except for relative humidity, particularly in Miami, and wind speeds. Results from this study can be used to determine equipment required for UA in different regions, meteorological parameters that most impact flight, and the best time for UA operations based on meteorological impacts.

CHAPTER 1

INTRODUCTION

The use of unmanned aircraft (UA) has steadily increased over the past several years and as more uses are found, it is anticipated that they will become a major tool for everything from surveillance to package transportation. In 2015, the Federal Aviation Administration (FAA) recognized the growing interest in UA and reiterated the importance of safety with UA use increasing in the National Airspace System (NAS). Since late 2015, FAA requires all UA weighing from a half pound to 55 pounds be registered under 'Unmanned Aircraft Systems (UAS) Flown by Certified Remote Pilots including Commercial Operators' (Part 107). According to FAA (2018), nearly one million UA were registered at the end of 2017. Registration data to the FAA estimates that nearly 100,000 UA are for commercial and consumer use. These UA are making their way into the mainstream of business as new and creative ways to use this technology are being introduced. The financial spending for UA development and total economic and employment impacts are anticipated to climb steadily. The contributions from UA development into our nation's infrastructure and the economic growth and job creation in the aerospace industry and to the social and economic progress of the citizens in the U.S. continue to impact our overall capabilities to increase UA use (Jenkins et. al. 2013).

Initial predictions see the largest growth in the areas of agriculture and public safety (Allianz 2016). Work is already being done in the area of surveying land to evaluate for storm, flood, or drought damage to crops and landscape. This is proving to be faster than any other method of transportation, and can be used to get to remote or unreachable locations due to natural disasters or road closures. Delivery services, such as providing medical supplies to remote areas, or even commercial delivery of packages are coming to the forefront for UA use. With this anticipated growth, it is apparent that there is potential for more UA in the air. Barriers, however, will affect this growth potential.

Safe UA operations depend upon reliable communications both from aircraft to aircraft and from pilot to aircraft. No one is in the cockpit with UA, so the needed information is transmitted back to a pilot on the ground through command and control (C2) information. This inherently adds a delay which may give the pilot in command (PIC) a very short time to react when looking at hazard avoidance and aircraft redirection. The PIC does not feel the wind or see weather phenomenon in the air immediately so must manage those risks throughout a flight, remotely. Of specific interest is the impact of weather related events on the ability to operate and control a small UA. The leading weather hazards for small UA include wind, turbulence, and clouds (Campbell et. al. 2017). Wind and turbulence can result in maneuverability challenges and even loss of aircraft control (LOC). Collision hazards are increased with reduced visibility, such as that resulting from clouds. Other hazards include excessive heat, cold, and moisture, which can result in aircraft component failures.

With the rapid growth in UA utilization, there is minimal historical data to evaluate their function with aircraft hazards over time. Much of the background requirements for UA use is based on research done on manned aircraft (Gupta et. at. 2013). Information specific to manned aircraft has flight grounding restrictions that are designed around take-off and landing conditions as well as mid-air flight. The National Transportation Safety Board (NTSB) identifies weather related issues within the NAS in terms of delays or take-off. Current grounding or delay issues for manned aircraft show nearly 70% of the commercial airline delays are caused by weather related situations and occur primarily during the summer months (FAA 2017). Since UA are lighter and are designed differently the applicability of this information to them is limited. In addition, the growth of UA use has primarily occurred within the past two decades which does not provide enough historical data for small UA. The study by Kulesa (2003) reiterates that weather delays comprise the majority of delays in all seasons, especially in the summer, which is similar to the information provided by FAA (2017). This shows consistency in the data for manned aircraft that is not yet established for UA. There is also rapid growth and advancement of new designs in the UA market so that no specific standard is available with which to draw conclusions or compare restrictions before the new technologies and designs are adopted. These UA add to the traffic volume in the NAS without adequate knowledge of risk for the pilot, the UA, or other aircraft.

Weather restrictions for manned aircraft are focused primarily on take-off and landing due to the design and weight of the aircraft. Wind is the primary concern for commercial aircraft, and in evaluating crosswind in manned aircraft Elliot (2013) noted that each airline has FAA-approved formulas and tables used to determine the maximum crosswind for a particular aircraft. Limitations on wind speed for manned aircraft are established by the FAA based on the weight of the aircraft and conditions of the runway, and manned aircraft require a relatively long distance for take-off and landing, which may influence grounding of the aircraft. UA operations may have different weather related concerns and it is not yet known if these same issues are more frequent or similar for small UA. The smaller size of UA means they do not require the same distances for take-off and landing. In addition, they are typically operated at low altitudes, keeping them in the boundary layer and its turbulence that contributes to gust events throughout the flight. Strong winds or wind gusts make maneuverability of an aircraft extremely challenging and sometimes impossible. Thus, weather related phenomenon can result in delays or cancellation of flights. As noted by Campbell et. al. (2017) for small UA, over 1500 cases of wind related incidents or accidents occurred and were reported in the 7-year time span from 2010-2017. With those reports, it was specifically noted that many of the wind related accidents were due to the effect of wind gusts rather than wind speed alone.

Reduced visibility, such as that resulting from clouds, increases collision hazards. Unless an appropriate waiver has been maintained (i.e., to Part 107), UA require visual line of site (VLOS) be maintained. Restrictions based on cloud cover, specifically low altitude clouds or ground level fog can determine if a UA can be launched. Under Title 14 of the Code of Federal Regulations (CFR) Part 107 (FAA 2018), a small UA must remain no closer than 500 feet below and 2,000 feet horizontally away from any clouds. Areas that have frequent low lying cloud bases or frequent convective events will have limited capacity for operating small UA. Coastal areas or low lying valleys experience fog that can remain through potential operating hours, thus limiting flight time or seasonal operations as well.

Temperature limits are in place for UA based on limitations of components that are used, including batteries, display, insulation and the engine, which can fail with extreme temperatures. Askelson et. al. (2018), evaluated environmental categories for manned aircraft performance and developed a 5 point Likert scale for UA operations. This provides a natural delineation of temperature and moisture conditions in which UA may be operated (and that may create operational challenges for small UA).

Each of the meteorological parameters has its own specific set of restrictions for UA flight. Currently, there are individual studies of how a UA responds to the hazard but no data on how frequent this hazard is encountered. Previous studies of the impacts for each of the parameters exist, but a compilation of the frequency which all of the hazards occur to develop an overall flight restrictions climatology has not been developed. If a restriction is in place for a flight, the PIC must request a legal waiver from the FAA to fly outside standard operating limits prior to take off. In the case where there are multiple hazards outside the safe operation parameters that are present simultaneously and if these operation limits overlap, there are multiple standards and restrictions to accommodate. The frequency of these restrictions must be established to understand limitations on UA operations.

This study evaluates the parameters of temperature, moisture, wind, and cloud base height both collectively and individually to create flight restriction climatologies. Hourly surface data from 1988-2018 are collected at five locations across the continental United States, which are selected for evaluation based on location and anticipated weather hazards: Bismarck, North Dakota (low temperatures), Riverton, Wyoming (winds), Oakland, California (low clouds and fog), Albuquerque, New Mexico (heat), and Miami, Florida (moisture). Thresholds for each meteorological parameter are set based on prior research and FAA regulations and are evaluated at each site. In order to evaluate these same conditions at heights above the surface, sounding data are collected within the same five locations.

The purpose of this study is to identify the frequency of potential weather-related restrictions for small UA, including the time of day and year at which they occur. It is anticipated that the results will reflect that UA operations, especially for small UA, will be significantly limited by weather hazards. It is also expected that the frequency of different hazards will depend upon season and time of day. Finally, it is expected that different locations will have different hazards that are most impactful.

CHAPTER 2

BACKGROUND

The increase in the number of UA operated for both personal and commercial use has put an emphasis on the need for information regarding their use. Information available describes both the uses of UA and indications of where further information is still needed. The types of UA designed today and the meteorological impacts on the current small UA are discussed.

2.1 Unmanned Aircraft Historical Review

UA are used for private, commercial, and military applications. The individual uses continue to grow. Development of UA and current uses are discussed subsequently.

2.1.1 History of Unmanned Aircraft Development

Original development of UA started in 1916 by American developers Lawrence and Sperry. This original aircraft was called the "aviation torpedo" and by using remote piloting could be flown over 30 miles (Gupta et. al. 2013). The concept of automatic steering control continued to be studied throughout the 1920's and 1930's, but focus on advancement of UA use did not occur until the 1950's. With the push for advancement and increased technologies in response to both the Vietnam War and the Cold War, support was directed at improving the use of UA. The initial designs were of small aircraft with special use of small engines that could be remotely piloted and carried video cameras that could provide images to the PIC on the ground at a different location. UA were designed to fly primarily indoors and avoid inclement weather (Gupta et. al. 2013); when atmospheric conditions were favorable, a UA was flown over foreign territory to scout the areas of interest.

Military contracts were established to utilize this technology and identify ways to implement them for surveillance purposes in remote or dangerous areas. The first official military use of this technology was in the early 1990's during the Gulf War (Gupta et. al. 2013). The National Aeronautics and Space Administration (NASA) led the advancement of this technology for military purposes with research support for the Predator Unmanned Aerial Vehicle (UAV). Additional progress in the 1990's included the use of UA for environmental measurements, with the most common technology known as NASA Environmental Research Aircraft and Sensor Technology (ERAST). The ERAST program studied engines and sensors in order to fly at higher altitudes and for longer durations (Cox et. al. 2006).

2.1.2 Unmanned Aircraft Uses

Advancements in UA development provided opportunities for improved imagery and stealth for military operations. These advancements are now moving into other areas for the same reasons. The convenience and benefits of operating small UA continues to expand how they are used for both personal enjoyment and commercial applications. The ability to use UA in low altitude airspace opened up options to avoid road closures and to cover difficult to reach areas for surveillance (Belcastro et. al. 2017). County and regional business find the benefit of surveillance photography after disasters helpful when evaluating damage in areas too difficult to reach via other means in the immediate aftermath of an event. Agricultural uses, such as monitoring of plant growth and fence line stability on ranches, are an improvement relative to previous use of manual labor (Allianz 2016). Even small commercial applications such as for delivering supplies or taking aerial photographs prove to be a cost efficient use of UA. These and other uses are expanding to more metropolitan areas and larger businesses, which make it important to understand weather hazards for UA.

The improvement in efficiency in carrying larger supplies, such as in the medical field where in September 2018 John's Hopkins University flew chilled blood samples 84 miles while maintaining strict temperature control (Daly 2018), is changing the weight and shape of UA as well as components onboard. Also, in the area of disaster readiness, multiple locations have used UA to evaluate flood damage or avalanche damage before opening an area. UA were used in finding people and supplies after hurricanes Harvey and Irma in 2017 (Werner 2017). UA are starting to be used for structural engineering. They are beneficial in getting to locations that are more challenging to reach, such as the outside of tall buildings and bridges (Park 2016). The uses of UA for imagery requires calm winds in order to retrieve focused pictures and videos. In addition, the equipment involved in imagery can be sensitive to environmental conditions and parameters, such as temperature and moisture, which must be evaluated prior to flight.

Lastly, UA are becoming more popular within larger businesses, such as Amazon and Google, for delivering packages and equipment (Barkho 2019). Most recently, a parent company of Google, Alphabet, began UA deliveries to customers in Canberra, Australia. The delivery businesses in Canberra are given permission to conduct deliveries while following policies regarding noise pollution and flight paths from air traffic regulators. The deliveries are reported to be completed within "minutes" of placing the order, proving quicker and more efficient, and the revenue estimate is $40 million Austrailian dollars in approximately 10 years for the company. Limitations for the deliveries include strong winds and other environmental factors as well as current FAA regulations. Due to current FAA regulations, such as flying a UA out of VLOS and weather related grounding, most businesses are still unable to use UA for package delivery.

2.2 Types of Unmanned Aircraft Designs

Depending on the intended use of UA, different designs are needed. This is based on weight, strength, and distance needed for flight. A familiar site over sporting events is the blimp, which is known to be one of the most simplistic UA. The purpose of these gas filled UA is to travel only short distances at a relatively fixed altitude and move slowly without a lot of weight. They have limited maneuverability and are easily programmed for pattern flight without concern for obstacles. At outdoor events, a major concern is the wind. Strong wind gusts can move a blimp off course and result in damage to property or injury to spectators and athletes so accurate forecasts of wind speeds is important to determine whether this type of UA can be flown. The need to carry cameras or supplies to different areas inspired the UA that are more commonly used today. There are two basic types of UA, fixed wing and rotary wing, and there is also a hybrid version. Each has its own susceptibility to meteorological conditions.

2.2.1 Fixed Wing

The fixed wing UA looks similar to the traditional manned aircraft and generally requires a runway for take-off and landing. Because their design is similar to that of manned aircraft, they are very streamlined and can be flown at speeds greater than 60 mph (Chapman 2016). Fixed wing UA also are designed for long duration and high altitude flying and are preferred for military use. They can carry large payloads over long distances and can be useful for both surveillance and transport of supplies.

According to a study by Burns (2015), fixed wing UA can be launched in surface wind speeds up to 25 mph before noticeable difficulty in maneuverability.

2.2.2 Rotary Wing

About 90% of the registered UA are considered rotary wing. Rotary wing UA have vertical take-off and landing capability and have greater maneuverability than fixed wing UA. These are more common for civilian or smaller independent commercial business because they generally have a shorter range than fixed wing UA but can be programmed to specific sites without need for an airport or landing strip. Rotary wing UA have several different designs in that the rotor can be placed in various positions on the UA, ranging from the top and tail rotors seen on manned helicopters to any configuration that allows the rotors to be tilted and work independently for greater position control (Gupta et. al. 2013). Rotary wing UA are usually smaller in size than fixed wing UA aiding in their ability to descend into smaller areas and hover, which results in a smaller battery, and can typically only be flown up to 30 minutes. Because of the fine tuning that is needed for these UA, they are commonly used for robotics and specific programming design and have a strong reliance on global positioning system (GPS) (Burns 2015). The sensors and cameras onboard a rotary wing UA limit the frequency with which they can be flown due to the need for suitable conditions for all components.

2.2.3 Flapping Wing

A more recent development is the hybrid of the fixed wing and rotary wing UA. These UA have additional flaps or wings that can be manipulated to work as a rudder much like a bird or insect wing (Gupta et. al. 2013). Specialty types of these UA are used as well, such as those that can take off vertically and hover much like the rotary wing UA design. Some hybrid UA can also tilt their wings to offer more maneuverability. Regardless of the mechanism for flight, advancements in UA design are based on need, with UA differentiated primarily by size and flight endurance.

2.3 Meteorological Parameters that Limit Unmanned Aircraft Flight

The rapid increase in UA has created a need for guidelines for their operations. Design of UA determines the limitations of where and when they can be flown. Weather continues to play a significant role in aviation accidents and incidents (Kulesa 2003). Different measures for the impact of wind, temperature, moisture, and cloud base height –along with sporadic and seasonal measures for icing and turbulence– are all based on sensor data provided for these guidelines. Environmental hazards to UA operation, such as the weather, are based on the area noting both geography and structures within the flight path that may alter flight data received by the PIC (Belcastro et. al. 2017). For many of the proposed uses of UA, this means that flight paths may be in more remote areas where data are not yet collected or they are being used after recent changes to landscape such as landslides or floods where there are changes in the established flight paths.

2.3.1 Wind

Perhaps the most recognizable weather phenomenon that contributes to flight delays is wind. High wind speeds and wind gust contribute to LOC of UA. A study by the FAA from 2003 - 2007 showed 56% of the reported UA accidents were due to wind (Ranquist et. al. 2017). As wind data are provided, the PIC needs to interpret and react to the information which can cause a delay in response time of maneuvering the aircraft. Determining the frequency of wind events that exceed the threshold for UA flight can provide parameters for safe operation. Small UA can typically be operated in winds up to 30 mph (13.5 ms^{-1}) (Huerta 2017). Wind speeds above 30 mph make small UA difficult to control and accidents much more likely. At these speeds, pilots can typically maintain position in the air, but motion in any one direction becomes difficult.

In addition to in flight wind restrictions, wind at the ground produces additional hazards so that even a moderate crosswind could exceed limits and make a takeoff or landing unsafe for all types of aircraft. The FAA has developed approved formulas and tables to determine the maximum crosswind parameters for all aircraft. In some cases, even a 5 mph crosswind could cause a UA to move off from a frictionless ice-covered runway (Elliott 2013). Surface wind speeds of over 15 mph make take-off and landing small UA extremely challenging. Wind and wind shear as hazards contribute to about 25% of the reported mishaps relating to environmental and location factors. Wind speed limits are well tested for manned aircraft and can be applied to large UA; however, current data on the frequency of impacts for small UA are not readily available.

The FAA supports nearly 850 sensor data information systems across the US. Automated Surface Observing System (ASOS) and Automated Weather Observing System (AWOS) are used across the United States, along with F420 anemometers and the low level windshear alert system. The PIC must interpret data from the sensors to determine if the conditions are adequate for flight in that area.

Many small UA are used to provide stable location imagery, and if they are fighting against strong winds even a GPS-programmed aircraft will struggle to adjust. Industrial inspections, real estate photography, agriculture, and insurance are the primary uses for UA imagery today (Allianz 2016). Agricultural photography typically uses set GPS patterns to examine a field, and an unpredicted strong wind gust could result in displacement of UA off course. A summary report by Adams

(2011) regarding UA usage for imagery post natural disaster noted downdrafts, wind shear, and turbulence from around buildings increased difficulties in UA stabilization. The eddied flow from structures at the surface significantly impact the wind speeds in the surrounding area. Additionally, changing wind speeds from the structures can cause a LOC and an increased risk of hitting another structure or object. The data provided in this summary identify impacts of varying wind speeds and how wind speeds limit the use of UA. This also takes into account how obstacles or structures in the path of the UA contribute to turbulence and airflow, which is discussed §2.3.6 herein.

2.3.2 Temperature

Extremes in atmospheric temperatures provide another challenge for UA operations. These extreme temperatures typically affect components, with one severe impact being communication being delayed or unavailable, thus impacting the ability of the PIC to interpret and react. Cold or over-heated components of the UA also affect battery life, so the actual operation may be shortened, or additional batteries may be needed adding weight to the UA. Additional concerns for UA, particularly for those used for surveillance with video and photographic capability, is the breakdown of visual displays owing to poor data transmission.

Through Alliance for System Safety of UAS through Research Excellence (ASSURE) research, categories have been established for evaluating small UAS Detect and Avoid (DAA) system hardiness to environmental conditions. These categories are based on DO-160 B (RTCA 1984) and MIL-STD-1472F (DoD 1999), which are two standards used to categorize manned aviation systems. Based on these, Askelson et al. (2017) established low temperature thresholds of 0°C, -20°C, -40°C, and -55°C; and high temperature thresholds of 20°C, 40°C, 50°C, and 85°C. Temperatures that are experienced are affected by both external factors, due to environmental conditions (which rarely exceed 40°C), as well as internal factors, which include heat generation owing to system operation.

2.3.3 Moisture

Though commonly paired with temperature extremes, moisture has its own inherent risks for UA operations. Humidity presents a problem if the moisture in the air condenses on the UA electronics (Ranquist 2017). Condensed water can cause electronics to short, which results in erroneous behavior, loss of functionality, or high amounts of heat output that could lead to a fire. Moisture that reaches the basic electronics onboard a UA can result in damage and delay in communication and C2. Maximum relative humidity specifications on UA range typically from 50% to 100%. During the early morning hours when temperatures are lower, humidity tends to be greater and the corresponding risk is higher. Different geographic locations have varying levels of relative humidity, so actual parameters need to be verified at the locations and procedures utilized to ensure that the electronic components can be operated safely.

As was the case for temperature, Askelson et. al. (2017) established categories using DO-160 B (RTCA 1984) and MIL-STD-1472F (DoD 1999). Limits are 80%, 90%, 95%, and 100%.

2.3.4 Cloud Base Height

Reduced visibility, such as that resulting from clouds, increases collision hazards. Under CFR Part 107, a small UAS must remain no closer than 500 feet below and 2,000 feet horizontally away from any clouds. The CFR Part 107 also states that a remote PIC cannot fly UA higher than 400 feet (ft) above ground level (AGL), unless flown near a structure for which one must not fly higher than 400 ft above the structure's immediate uppermost limit, as illustrated in Figure 1. A study by Wallace et. al. (2018) showed that about one fifth of the UA flights from 2014-2017 are flying higher than the safe altitude for the prescribed areas. These limits are set to ensure a UA pilot always has a VLOS with their aircraft and to prevent interference with manned aircraft, which cannot fly below 500 ft without waivers.

The National Transportation Safety Board (NTSB) issued the first accident report of a UA-involved midair collision with a manned aircraft on 21 September 2017 due to a UA PIC who was intentionally flying beyond VLOS and did not follow FAA regulations and safe operating practices (English 2017). The UA PIC was unable to see or hear approaching helicopters and was unaware he was flying in an area with a Temporary Flight Restriction (TFR). This accident was not due to low cloud bases, but rather lack of VLOS.

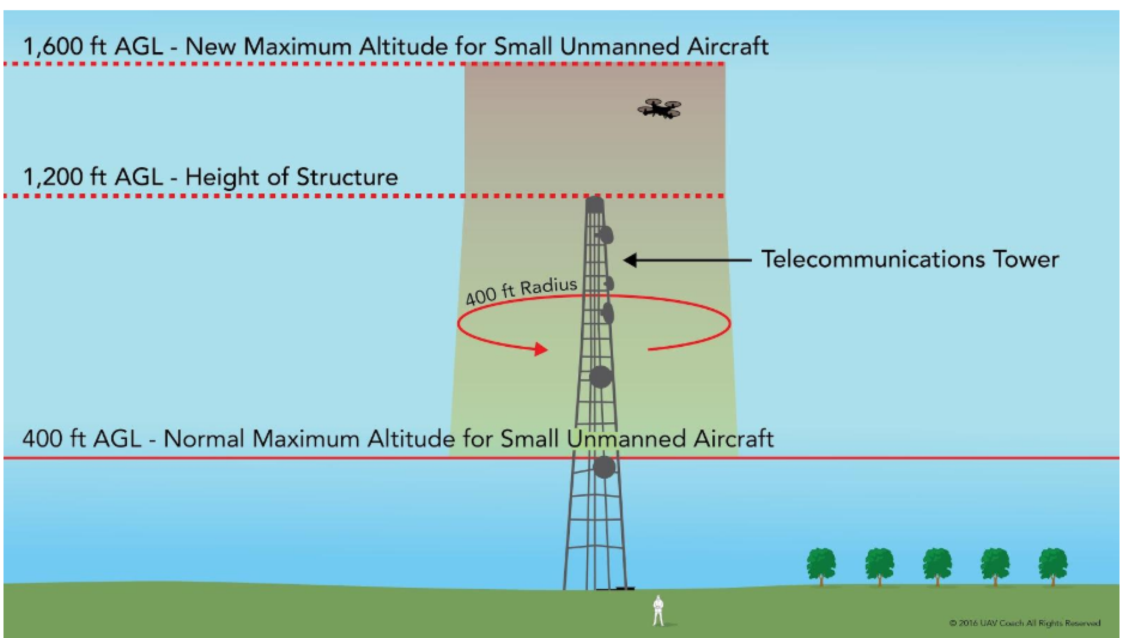

Figure 1: From Drone Pilot Ground School, the height operating limits for UA around a structure. A 400 ft radius provides additional airspace for unmanned aircraft.

2.3.5 Icing

Ice formation on an aircraft will have multiple negative effects, including a reduced flight time, reduced lift, increased drag, and increased weight. Small water droplets from fog and stratus clouds, which can form anywhere from ground level to ~2000 m, can layer on UA as rime ice in subfreezing conditions (Politovich 2015). This rime ice forms on the leading edge of UA components and can alter balance and control of UA, leading to crashes. Ranquist (2017) stated that for general UA operation, water droplet size is less important than the amount of liquid water content in the atmosphere.

Icing on sensor components and batteries affect performance and the distance UA are able to travel. Although icing is not specifically evaluated within this study, UA commonly operate in the area at the icing threshold and just below the small aircraft limits and are at the cusp of limits to seeing the initial effects from low lying clouds. Further research on icing specific to UA operation in low altitude environments is ongoing.

2.3.6 Turbulence

The unpredictability of turbulence can cause LOC of an aircraft and can result in crashes. Turbulence involves irregular patterns of wind gusts resulting from a wide range of weather conditions, such as terrain changes, weather fronts and boundaries, wind flow around structures, and daytime heating (Kulesa 2003). Wind shear causes turbulence at any altitude, and aircraft experiencing turbulent conditions are susceptible to damage and decrease in the efficiency of the flight. Through tests performed by Clark et. al. (2017), it is determined that wind gusts and turbulence contributed to the majority of reported wind related aircraft accidents from 2010-2017.

It is anticipated that topography will have a significant impact on wind gusts. These wind gust speeds contribute to FAA limitations for grounding UA or cause delays or deviations from the pre-programmed GPS path. Current weather models are one means for estimated timing and location of wind gusts exceeding the recommended parameters for safe UA flight.

In addition to elevation changes, structures at the surface affect the direction and speed of wind gusts. Wind gusts are studied on and around stationary objects so information can be applied to objects such as UA or manned aircraft. Calvetti et. al. (2012) investigated wind gusts and convective updraft and downdraft effects within the range of pylons less than 500 ft tall. Calvetti et. al. (2012) utilized the Weather Research and Forecast (WRF) model to predict the frequency of wind gusts and their impact on the standing pylons. In their initial data, it was determined that the predicted time of the wind gust event was up to an hour away from the actual event. These data, along with various other studies provide information regarding the accuracy of wind gust forecasting, and indicate that current models cannot accurately forecast the timing of wind gusts around structures at the surface. While UA usage increases, the plan is to fly in and around metropolis areas. Without accurately forecasting turbulence in these areas, the times when UA can safely be operated is uncertain.

2.4 Past Research on Manned Aircraft

Much of the data used to establish parameters for flight operations comes from studies using manned aircraft since there are very few resources specifically placed and designed to measure actual UA flight. Kulesa (2017) noted that weather contributes to 23% of all aviation accidents and are identified by the NTSB in terms of delays or take-off. The total weather impact is an estimated national cost of $3 billion for accident damage and injuries, delays, and unexpected operating costs. Current grounding or delay issues for manned aircraft show that nearly 70% of the commercial airline delays are caused by weather related situations (FAA 2017). Many of the delays noted occur during summer months with extended daylight hours and occur in cities with busy airports where multiple sensors are used to collect data. This may relate to high volume as well as weather patterns and convective activity. Airports that have documented the greatest amount of delays are in the larger cities of Chicago, New York, Atlanta and San Francisco (FAA 2017), which are also noted to have some of the most extreme weather patterns for wind, extreme temperatures and low cloud base.

The largest impact to airports is delays that impact flow and traffic. Data specific to weather are collected at airports using specific sensors and static locations which gives limited information regarding the overall conditions for operations. It has been recognized that limitations to current data are related to sensor information being provided at one location along a runway. Wind speed and gusts can vary significantly at different points along the runway and at varying heights as the aircraft approaches or departs the runway. Lack of consistent reliable data is the motivation of Clark et. al. (2018) to provide more applicable information through the FAA's NextGen system. The FAA Information Display System compiles Meteorological Terminal Aviation Routine Weather Report (METAR) data as well as information from other sources including ASOS and AWOS to a single display (Clark et. al. 2018). The weather information is then used by manufacturers to set limitations or parameters on flight requirements. Wind uncertainties are driven by four primary causes: observer inconsistency, temporal translation error, spatial translation error, and deficiency in interpretation of data. In 2004, the nation made a significant stride toward standardizing the ASOS system as the primary model for obtaining weather information and expanded it to include automated information on not only wind, but temperature, fog and cloud cover, and precipitation. Specific guidelines for use of these systems was established by the National Weather Service (NWS) to ensure commonality in reporting. In the Campbell et. al. (2017) study, shortfalls of the data were discussed, with specific recommendations related to increased amount of sensors and placement of sensors provided.

Wind related hazards contribute to the majority of documented weather delays and incidences in manned aircraft. When evaluating the impact wind has on manned aircraft, four specific components of wind are evaluated: crosswind component – the side element of the wind, headwind – amount of wind from the front of the aircraft, tailwind – amount of wind from behind the aircraft, total wind – total speed of the wind. These impact both take-off and landing principles as well as timing of flight operations. Limitations on wind speed for manned aircraft are established by the FAA based on the weight of the aircraft and conditions of the runway, such as moisture and visibility. Manned aircraft require a relatively long distance for take-off and landing, which may be a factor in grounding of the aircraft.

For icing, a study in the 1990's by the NTSB indicated that in-flight icing contributed to approximately 11% of all weather-related accidents among general aviation aircraft (Kulesa 2017). Structural icing on control surfaces increases aircraft weight, degrades lift, generates false instrument readings, and compromises control of the aircraft leading to a loss of control of the aircraft.

Visual Flight Rule (VFR) flights are also a concern for manned aircraft, as the plot in the aircraft must be able to see the surrounding area. In 1991, the University of Illinois used simulated weather conditions to test twenty VFR rated pilots. When deprived of visual contact, each pilot experienced LOC. On average, it took approximately 178 seconds giving each pilot less than 3 minutes to live in the simulation after entering a cloud (Kulesa 2017). Additionally, reduced visibility places pilots at risk for collisions.

2.5 Missing Information for Unmanned Aircraft

Research on weather hazards have identified potential risks for manned aircraft, but this does not necessarily translate equally to UA use. Special characteristics of unmanned aircraft need to be analyzed and identified specifically for UA operations (Belcastro 2017). The FAA has placed restrictions on the locations and certain weather conditions in which UA can operate. While many tests on manned aircraft have been completed to determine the frequency of certain weather hazards impacting flight, this information is generally not available for small UA.

The lack of information specific to UA use is further driven by the parameters established for manned aircraft flight hazards being measured at locations specific to their operations. Namely, the data available and the models used to establish the thresholds are from airport and runway locations where the use of small UA is generally prohibited. Data are not typically available for remote areas or at lower altitudes where UA operate. Specific parameters can limit UA operations, but the missing data for these parameters are needed to determine how frequently these limitations are reached.

Current FAA regulations are based on models of atmospheric conditions measured at locations where sensors are currently available for aviation research. These models can be used for multiple weather phenomenon. Output from the simulations performed by Roseman (2019) was used to identify the maximum impact of weather hazards including wind speed, extreme temperatures, and precipitation. The data were further developed to offer specific weather advisories to UA pilots in order to determine if conditions are acceptable to operate. By looking at wind, temperature, cloud heights, and moisture content, a climatology of the frequency of thresholds reached will be evaluated.

CHAPTER 3

DATA

This study utilizes the current FAA parameters for UA, along with thresholds identified in prior research to determine the frequency at which UA operations may be restricted. Data from 1988 - 2018 are collected at five locations across the continental United States, each selected for their unique locations and expected weather discussed in §4.2. Surface data collected at each location are used to determine the frequency with which temperature, moisture, wind speed, and cloud base heights exceed specified thresholds. In order to evaluate these same conditions at heights above the surface, sounding data are collected at the same five locations.

3.1 Surface Stations

The surface data are collected from the Integrated Surface Database (ISD) through the National Centers for Environmental Information (NCEI). ISD provides data from as far back as 1901, with an increased volume of data in 1940 and 1970, and at over 35,000 stations across the world (NCEI-ISD 2019). All geophysical surface observations globally, including METAR, SPECI and Surface Airway Observation (SAO) reports, are combined in ISD and sorted by location. Many meteorological parameters are included in ISD, such as: temperature, dew point, wind speed and direction, wind gust, cloud data, present weather, visibility, and other elements observed at each station. For the purpose of this study, temperature, dew point, wind speed, wind gust, and cloud data are collected at each location.

Within each record, a section of control data provides information regarding the date, time, and location of the data. Immediately following the control data is the mandatory data section. The mandatory section, which has a fixed length, includes the most basic meteorological parameters, such as temperature and wind. The additional data section, which follows the mandatory data section, has variable length based upon information of significance that is included in the report.

3.2 Sounding Data

Radiosonde and pilot balloon observation data are combined into the Integrated Global Radiosonde Archive (IGRA) through NCEI. The data are from as early as 1905 from over 2,700 stations around the world (NCEI-IGRA 2019). Individual soundings, monthly means, and sounding-derived parameters are individually organized and separated into one file per station. Meteorological parameters provided include pressure, geopotential height, temperature, relative humidity, dew point depression, wind speed, and wind direction. The observations for each sounding vary in temporal and vertical resolution. The data are available at the standard pressure levels. Mandatory pressure levels and additional levels are provided when the temperature and moisture values show a significant change from linearity. The mandatory pressure levels are defined as the surface, the highest level achieved, one level between 110 hPa and 100 hPa, the tropopause, the bases and tops of temperature inversions and isothermal layers greater than 20 hPa in thickness and at pressures greater than 300 hPa, the bases and tops of all inversion layers with temperature changes of 2.5 °C or 20% relative humidity at pressures greater than 300 hPa, and levels delineating layers with missing or doubtful data (Baker et. al., 1997). Additional wind data are provided at significant levels which are selected similar to those for the thermodynamic variables. Levels are selected based on a 5 ms^{-1} (10 knot) wind speed, or 10 degree wind direction change from linearity. If the wind speed is less than 5 ms^{-1} the winds are not considered while selecting additional levels. Calculations of wind speed are from the position of the balloon, using earth spherical coordinates.

The Federal Meteorological Handbook No. 3 (FMH3) dictates federal standards for obtaining radiosonde and pilot balloon observations and for processing the observations (Baker et. al. 1997). The NCEI, along with all United States government agencies or facilities that collect radiosonde and pilot balloon observations, follow the data collection and archiving rules from FMH3.

CHAPTER 4

METHODOLOGY

The frequency of times a UA cannot operate or has restrictions due to meteorological parameters is evaluated over a 30-year time frame at five locations across the United States to determine potential limitations to UA flight. Meteorological parameters of temperature, moisture, wind, and cloud base height are considered collectively first and then individually to create a report of the frequency of restrictions.

Data from surface stations provides information regarding the frequency with which defined thresholds are met. UA are also influenced by weather above the surface, and sounding data are used to evaluate the frequency of threshold exceedance at various heights. The data are processed and quality control is completed on all surface stations and soundings as discussed subsequently.

4.1 Processing Data

4.1.1 Surface Stations

ISD provides a code in the control data section that distinguishes the type of geophysical surface observation provided. For this study, hourly observations from SAO through 1995, and METAR observations starting in 1996 are used for evaluation. The meteorological parameters provided in the mandatory data and additional data sections have a corresponding quality code that is provided by automated quality control (QC) software. The ISD QC process involves two phases. The first check uses quality assurance to test the input data file to detect whether the data provided can be merged into the composite observations (Lott 2004). The second phase includes algorithms used to check for inconsistency of values and systematic errors in the data. All erroneous data, defined by the QC check for each meteorological parameter, are removed from the dataset.

4.1.2 Sounding Data

IGRA provides quality assured data by following the QC procedures outlined in Chapter 4 of FMH3 (Baker et. al. 1997). Data anomalies encountered when analyzing pressure, temperature, humidity, and wind measurements are defined as erroneous or doubtful data. All erroneous data are eliminated during the QC and are considered 'missing data' henceforth (Baker et al. 1997). For this project, all data that are considered erroneous or doubtful are removed from the sample. However, other meteorological parameters at each level may still be provided.

To evaluate how the meteorological parameters change at various heights above the surface, the data are interpolated to geopotential heights from the surface to 1000 ft AGL in 100 ft increments. To interpolate the sounding data, the procedure from Askelson (2002, §3.2.3.1) is followed. First, pressure p, temperature T, and dewpoint temperature T_d data are retrieved from mandatory and significant levels. The virtual temperature T_v, is calculated at all pressure heights using the approximation

$$T_{\mathrm{v}} = T(1 + 0.608 r_{\mathrm{v}}) \tag{4.1}$$

where r_v is the mixing ratio calculated using the vapor pressure e, from T_d. The calculated T_v values follow the assumption that T_v varies linearly with $\ln p$, so the pressure is calculated for each geopotential height. The height z_m lies between the sounding levels Z_i and Z_{i+1} and is used to calculate p at each height using R_d the dry gas constant (287.04 J Kg^{-1} K^{-1}). The solution for p is,

$$p = \begin{cases} p_i \exp\left[\dfrac{T_{vi} \pm \sqrt{T_{vi}^2 + \frac{2g_0}{R_d}\frac{T_{vi+1}-T_{vi}}{ln(\frac{p_i}{p_{i+1}})}(z_m - Z_i)}}{\frac{T_{vi+1}-T_{vi}}{ln(\frac{p_i}{p_{i+1}})}}\right] & T_{vi+1} \neq T_{vi} \\ p_i \exp\left[\frac{g_0(Z_i - z_m)}{R_d T_{vi}}\right] & T_{vi+1} = T_{vi} \end{cases} \tag{4.2}$$

and is dependant on whether or not $T_{v_{i+1}}$ is equal to T_{v_i}. With the pressure values known at each height, T_v values are determined by linearly interpolating T_v with ln$p$ using,

$$T_{\rm v} = T_{\rm v1} + \frac{T_{\rm v2} - T_{\rm v1}}{lnp_2 - lnp_1}(lnp - lnp_1) \tag{4.3}$$

where subscripts 1 and 2 represent two levels in the atmosphere (1 represents a lower altitude than 2), and p is the pressure level at which interpolation is being performed. It can be shown that T and r_v values show a consistent linear variation with T_v, where environmental T values are determined by interpolating them as a function of ln$p$ from the sounding data (Askelson 2002). From the interpolated T and T_v values, the environmental r_v values are calculated using,

$$r_{\rm v} = \frac{\frac{T_{\rm v}}{T} - 1}{\frac{1}{\epsilon} - \frac{T_{\rm v}}{T}} \tag{4.4}$$

where $\epsilon = R_d \backslash R_v$, with R_d the dry gas constant (287.04 J Kg^{-1} K^{-1}) and R_v the gas constant for water vapor (461.5 J Kg^{-1} K^{-1}). The interpolated relative humidity values are calculated at each height using the dew points associated with the r_v values.

Wind data from IGRA are provided at all standard pressure levels. Additional wind data are provided at geopotential heights collected during the observation where either the wind direction or wind speed does not follow a linear ln$p$ pattern (Baker et al. 1997). While interpolating data, Schaefer and Doswell (1979) found that because a vector is a directed quantity, the interpolation of the magnitude and direction does not provide the same results as the interpolation of the individual components. Thus, for this study all wind data are sorted according to the associated geopotential height and the wind speeds provided for each sounding are broken down into Cartesian velocity components such that,

$$u = speed * [-sin(\theta)] \tag{4.5}$$

and

$$v = speed * [-cos(\theta)] \tag{4.6}$$

The individual components are interpolated and combined to calculate the actual wind speed, U, using $U = (u^2+v^2)^{1/2}$ to provide the interpolated wind speed value for each height.

4.2 Observation Locations

Climatologies are developed at five locations across the United States based on geographic location and anticipated weather. The colder climate of Bismarck, North Dakota is expected to reach thresholds set for low temperatures a significant fraction of the year, and will result in flight restrictions, primarily in the winter months. The mountainous terrain of Wyoming provides for stronger winds in Riverton, Wyoming and is expected to reach wind speeds above the thresholds set for UA to fly. Oakland, California observes dense fog and low lying clouds frequently throughout the year and with limitations to the height at which a UA must be below a cloud base, the low-lying clouds restrict UA flight. Along the northern edge of the Chihuahuan Desert, Albuquerque, New Mexico reaches temperatures above the thresholds set for high temperatures for UA. The high temperatures in Albuquerque are likely to peak in the summer months and are expected to significantly restrict UA flights. Lastly, Miami, Florida experiences significant moisture throughout each day, and will see relative humidity values above the threshold set for UA operations. Although each location is chosen for the likelihood of reaching a particular meteorological parameter, all of the meteorological parameters are examined at each location. The selected locations provide surface data and sounding data as early as 1988, and the surface and sounding observation locations are within a 10 mile radius of each other.

The station identifiers are provided through the NCEI database. Each location has a similar station identifier for their surface data and sounding data, with the identifiers in Bismarck as 727640 and 72764, respectively. Similarly, Oakland, Albuquerque, and Miami have identifiers of 72493, 72365, and 72202, respectively. In Riverton, the location for balloon launches changed in 1995, and with that change a new station identifier was assigned. The data from the surface station identifier, 725765, is the same as the sounding data from prior to 1995, and the data after 1995 uses the station identification, 72672. Both identifiers are combined and used for a complete 30-year representation of the area.

Although each location has reports from 1988 to 2019, there are occurrences where no data are available for a designated location. At the end of 1995 the surface station observations were converted from SAO reports to METAR reports and data from 1996 - 1997 is not provided for Riverton, Albuquerque, and Miami.

4.3 Meteorological Parameters

The current FAA parameters for UA, along with thresholds identified in prior research are used to determine the frequency at which UA operations may be restricted. The frequency of reaching these thresholds is evaluated to determine the parameter with the greatest impact to UA flight operations at each location.

Based on the study by Huerta (2017), small UA are inoperable in wind speeds over 30 mph at either the surface or aloft. Wind speed values over 15 mph at the surface limit maneuverability of UA and may result in difficulty with take-off and landing. For this study, UA flight restrictions are evaluated for wind speeds of 15 mph, 20 mph, 25 mph, and 30 mph. Wind speeds over 30 mph will be deemed as inoperable for UA flight for this study, whereas wind speeds less than 15 mph are deemed to not cause restrictions to UA flight.

The temperature and moisture limitations are established by Askelson et. al. (2017). Information regarding the UA systems is difficult to obtain because of unknown information owing to a lack of testing or because the information is not publicly-provided (Askelson et al. 2017). Askelson et. al. (2017) established, for the sake of scoring systems, UA temperature ranges of 0°C to 20°C, -20°C to 40°C, -40°C to 50°C, and -55°C to 85°C. Therefore, the thresholds set for this study are temperatures greater than 20°C, 40°C, 50°C, and 85°C and temperatures less than 0°C, -20°C, -40°C, and -50°C. It is noted that it is unlikely that the ambient temperature is above 40°C, however enclosed spaces of an aircraft continue to heat due to moving mechanical parts and may become overheated. Similarly, relative humidity thresholds of 80%, 90%, 95%, and 100% are used, where UA are deemed not to be flown in 100% humidity and relative humidity values less than 80% do not impact UA flight.

Lastly, due to FAA regulations that limit UA flight to below 400 ft AGL and 500 ft below cloud bases (Part 107), cloud bases are evaluated at heights that will restrict or ground all UA operation. Frequency of cloud bases at 500 ft, 600 ft, 700 ft, 800 ft, and 900 ft are evaluated from surface station data. Cloud heights below 500 ft are considered inoperable, and cloud bases above 900 ft do not limit UA operations.

CHAPTER 5

RESULTS

This study is designed to identify the frequency of reaching meteorological-parameter based thresholds for restricting UA flight and the times at which they occur.

For each of the five selected locations, a cumulative representation of the data shows the frequency with which these weather hazards reach their specific limits and which hazard has the largest impact for each location. The data are evaluated to establish frequencies with which temperature, moisture, wind, and cloud base height reach UA operational limits, and reflects both seasonal and diurnal variations.

Following the quality control procedure discussed in §4.1 and removing any missing or faulty data, the data file sizes are reduced by an average of about 1%. Table 1 displays the total percent of data that are used for observations at each location, as well as a breakdown of data for each month to determine if any one month had significantly reduced data that would skew the results. At the surface, Riverton has the highest percent of data that is removed with almost 2% of the data missing or faulty. Riverton and Oakland have a greater increase in missing and faulty data in the winter months (December, January, and February), however this does not reach over 3% so all data is observed equally. The quality assured sounding data had accurate data over 99% of the time at all locations, with Bismarck and Miami having accurate data over 99.9% of the time.

The percent of time a UA can operate, operate under restrictions, or cannot operate based on thresholds defined in §4.3 are plotted for each selected location. These percentages are categorized by month and hour as well as by meteorological parameters to determine what conditions have the greatest impacts on UA flight.

Table 1: Percentage of data that was retained following the quality control procedures characterized by month and location for both surface and sounding data.

Surface Data	**Total**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Bismarck	99.66	99.56	99.84	99.90	99.32	99.41	99.63	99.65	99.80	99.53	99.67	99.71	99.91
Riverton	98.09	97.33	95.69	98.67	98.90	98.54	98.70	98.81	99.03	98.84	98.30	97.16	96.93
Oakland	98.97	98.53	96.80	99.55	99.56	99.25	99.14	99.27	99.32	99.27	98.93	98.91	99.00
Albuquerque	99.87	99.97	99.92	99.89	99.87	99.84	99.81	99.85	99.94	99.89	99.88	99.86	99.88
Miami	99.87	99.89	99.94	99.94	99.93	99.86	99.87	99.89	99.88	99.68	99.85	99.88	99.87
Sounding Data	**Total**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Bismarck	99.95	100.00	100.00	99.95	100.00	100.00	99.95	99.95	99.90	99.84	99.95	99.89	100.00
Riverton	99.87	99.89	99.88	99.90	99.84	99.47	99.89	99.89	99.95	99.89	99.95	100.00	99.89
Oakland	99.49	99.43	99.38	99.84	99.95	99.84	99.73	97.07	99.79	99.62	99.95	99.73	99.58
Albuquerque	99.57	99.90	99.22	99.01	99.78	99.90	99.25	98.30	99.85	100.00	100.00	99.95	99.74
Miami	99.98	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.93	99.93	99.93	100.00	100.00

5.1 Surface Stations

Figure 2 shows the aggregated surface observation results across all 30 years for each station, categorized by the amount of time UA can operate, operate under restrictions, or cannot operate. Albuquerque and Riverton have the largest percentage of times where UA can operate without any restrictions, at 48.8% and 41.0%, respectively. Oakland has the most periods where UA cannot operate, 17.2% of the time. While UA cannot operate only 1.7% of the time in Miami, over 90% of the 30-year time period there are parameters that cause some restrictions on UA.

The percentage of time UA can operate, operate under restrictions, or cannot operate, are shown by month of the year in Fig. 3. Bismarck, Riverton, and Albuquerque have a bimodal distribution of the times UA can operate, with peaks in the Spring and Fall seasons (Figs. 3a,b,d). The times when a UA can operate decreases significantly in the winter and summer months in Bismarck, with a larger decrease in the amount of time a UA can operate in the winter resulting in UA flight reduced to less than 10%. Of the time a UA can operate in Albuquerque, the summer months show a decrease in flight operations with a minimum of 9.7% in July. In Oakland, the time a UA cannot operate peaks during the late summer months from July to September, with the highest percent of times where a UA cannot operate at 35.6% in August (Fig. 3c). Miami averages the highest percent of flight restrictions, at ~98% from May through September, which make up the majority of the high percentage of total flight restrictions at that location.

Similarly, Fig. 4 displays the amount of time UA can operate, operate under restrictions, or cannot operate by time of the day in UTC. Each of the stations show an increase in the percent of time a UA cannot operate between 12 UTC and 18 UTC, with Bismarck and Oakland showing the highest percentages at 14.3% and 31.6%, respectively (Figs. 4a,c). The time a UA can operate in Albuquerque is highest, exceeding 50% from 04 UTC to 14 UTC, with restrictions increasing at 18 UTC.

To determine the primary reason for flight restrictions and groundings at each station, the surface observations are further categorized by meteorological parameters and shown in Fig. 5. Bismarck and Riverton have low temperatures as a primary restriction to UA operation at 33.8% and 29.4%, respectively (Figs. 5a,b). Relative humidity and low cloud bases limit most of the flights in Oakland at 44.9% and 23.3%, respectively. Figure 5e shows that Miami has the highest percentage of flight restrictions or grounding in one category, that being high temperatures 87.2% of the time.

The meteorological parameters are categorized by month to identify any monthly or seasonal patterns for each station, which is shown in Fig. 6. The percent of time UA have restrictions and grounding for each parameter are evaluated individually and the totals can be greater than 100%, where multiple parameters can affect UA flight operations at the same time. Low temperatures and high relative humidity values were the primary factors for flight restrictions and groundings in Bismarck (Fig. 5a). The impact from low temperatures occurs primarily from October to March, with the highest impact above 80.0% in December, January, and February; however, the percent of flight restrictions due to relative humidity is relatively constant throughout the year (Fig. 6a). Although high temperatures only cause flight restrictions and grounding about half as often as low temperatures in Bismarck, the restrictions are mostly concentrated across only three months (i.e., June, July, and August), meaning that UA are restricted by high temperatures nearly as often as low temperatures even though low temperatures occur more commonly. Riverton has a similar distribution of flight impacts, with temperature restrictions being the leading cause for UA flight restrictions and grounding. Temperature restrictions are the leading driver of the bimodal distributions present in Figs. 3a,b for Bismarck and Riverton, respectively. The primary factors causing flight restrictions in Oakland are high relative humidity values and low cloud bases. These variables are relatively consistent throughout the year, with a slight peak in July and August (Fig. 3c). The increase in both relative humidity and cloud base restrictions occurs while Oakland experiences the greatest percentage of time a UA cannot fly. Albuquerque and Miami both have the greatest amount of UA restrictions or groundings due to high temperatures (Figs. 5d,e), but it is clear that the majority of these restrictions only occur during the summer months in Albuquerque (Fig. 6d), while high temperatures are a challenge year-round in Miami. Miami also has a greater restriction percentage due to high relative humidity throughout the year, which when combined with the restrictions caused by high temperatures lead to restrictions being in place almost 100% of the time April through October (Fig. 3e). Even though winds were not the primary restriction at any location, Figure 6 shows that wind has an effect on the time UA can operate with an increase in flight restrictions and groundings during the springtime (e.g. March, April, May) at all locations.

The meteorological parameters are further categorized by hour to identify any diurnal biases in each station (Fig. 7). Although the impact from high relative humidity is consistent throughout the year in Bismarck (Fig. 6a), the majority of restrictions imposed by high relative humidity values occur overnight and into the very early morning hours. During these times, UA operations are limited; therefore, the impact of relative humidity on UA operations is minimized even though it is the largest contributor to UA restrictions in Bismarck (Fig. 5a). The low temperature restrictions are relatively consistent throughout the day in both Bismarck and Riverton, with a slight peak due to low temperatures at 12 UTC before sunrise (Figs. 7a,b). Oakland has the greatest impact from low cloud bases and high relative humidity values in the overnight and morning hours (Fig. 7c). As daytime shortwave heating ends, temperatures cool to saturation and fog and/or stratus clouds commonly develop with the typically light overnight winds. The relative humidity and cloud restrictions rapidly dissipate after 15 UTC as diurnal heating warms the air, which allows UA to fly with limited restrictions by 18 UTC. Albuquerque's high temperature and wind restrictions are directly correlated with the diurnal cycle. As daytime heating warms the air, the amount of restrictions due to high temperature increases and peaks at 23 UTC (Fig. 4d). The wind speed restrictions similarly follow the diurnal cycle. The boundary layer becomes well mixed due to strong heating and parcels with high momentum aloft are able to descend dry adiabatically down to the surface. Since the restrictions in Albuquerque are so directly tied to the diurnal cycle, the majority of UA restrictions are limited to the summer months during peak heating. Miami has consistently high temperature restrictions throughout the day; however, the impact from high relative humidity values is limited to the overnight and morning hours, where the humidity values rapidly decrease after 12 UTC due to diurnal heating, effectively eliminating any UA restrictions by 14 UTC (Fig. 4e).

The locations most impacted by each meteorological parameter causing UA operation restrictions or grounding are shown in Fig. 8. Bismarck and Riverton have the highest percent of time low temperatures are a restriction for UA operations (Figs. 8a,b). The impact from low temperatures occurs primarily from October to March, as seen in Fig. 6. Both Bismarck and Riverton have temperatures below -20°C a fraction of the 30-year time frame; however, no locations have temperatures below -40°C. High temperatures cause the most restrictions in Miami, with restrictions to UA operations over 80% of the time. Although each station had restrictions due to high temperature ~10% of the time or more, none of the stations had ambient temperatures above 40°C during the 30-year time period, however the components within the aircraft could still emanate heat and the UA experience higher temperatures. High relative humidity is a primary concern in the overnight and morning hours, while the temperatures are lower (Fig. 7), and Bismarck, Oakland, and Miami have restrictions due to high relative humidity over 30% of the time. About 15% of the time the relative humidity at these locations is over 90%, with Oakland having the highest percentage of time with relative humidity values over 100% (3.4% of the time). Wind restrictions to UA operations are similar at each location, with Bismarck having the highest percentage of wind restrictions at 16.0%. followed by Albuquerque and Riverton at ~11%. Each of these locations of Bismarck, Albuquerque, and Riverton had wind speeds above 25 mph ~2% of the time. Miami has the least amount of wind restrictions and most of the time wind speeds do not exceed 20 mph (Fig. 8d). Low cloud bases are the secondary cause to UA restrictions in Oakland (Fig. 5c). Figure 8e shows the highest percent of restrictions due to low cloud bases occurs in Oakland and Bismarck at 24.0% and 15.7%, respectively. Of the times when restrictions due to low cloud bases are present in Oakland, 17.1% of the time the cloud bases are lower than 500 ft AGL and UA cannot operate without an appropriate waiver obtained. Figure 2 shows that UA are unable to operate in Oakland 17.2% of the time; therefore, the restrictions due to low cloud bases are the primary cause for UA grounding in Oakland.

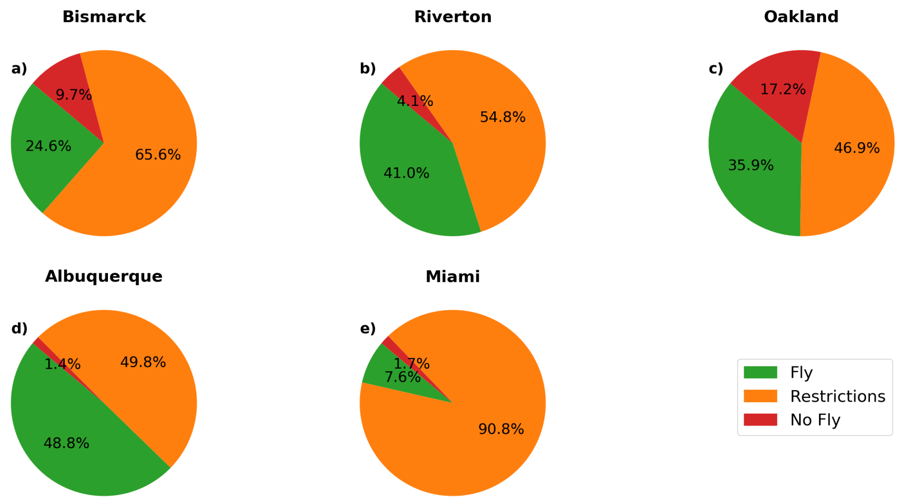

Figure 2: Percentage of time UA can operate (green), operate under restrictions (orange), or cannot operate (red) for a) Bismarck, b) Riverton, c) Oakland, d) Albuquerque, and e) Miami.

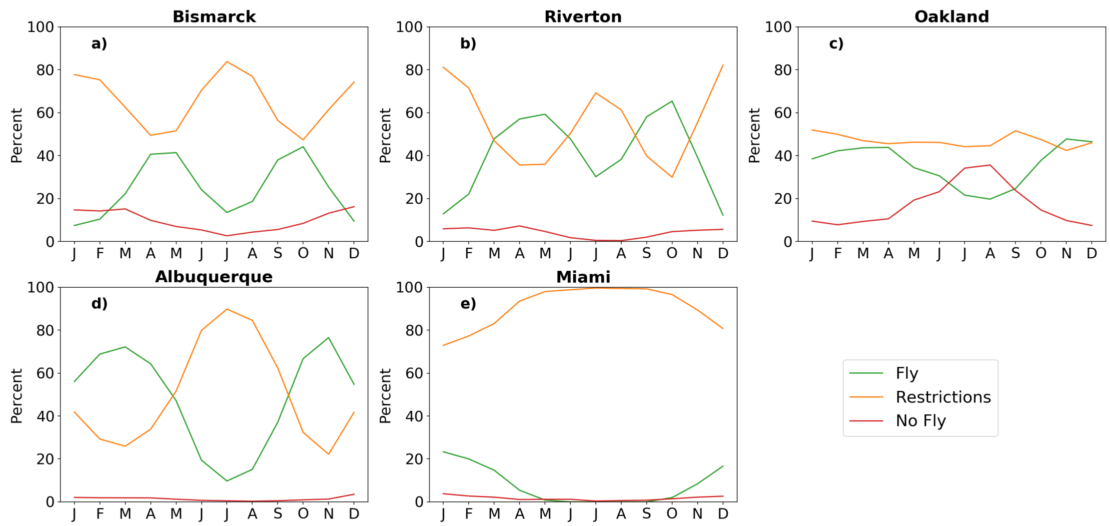

Figure 3: Percentage of time UA can operate (green), operate under restrictions (orange), or cannot operate (red) for each month for a) Bismarck, b) Riverton, c) Oakland, d) Albuquerque, and e) Miami.

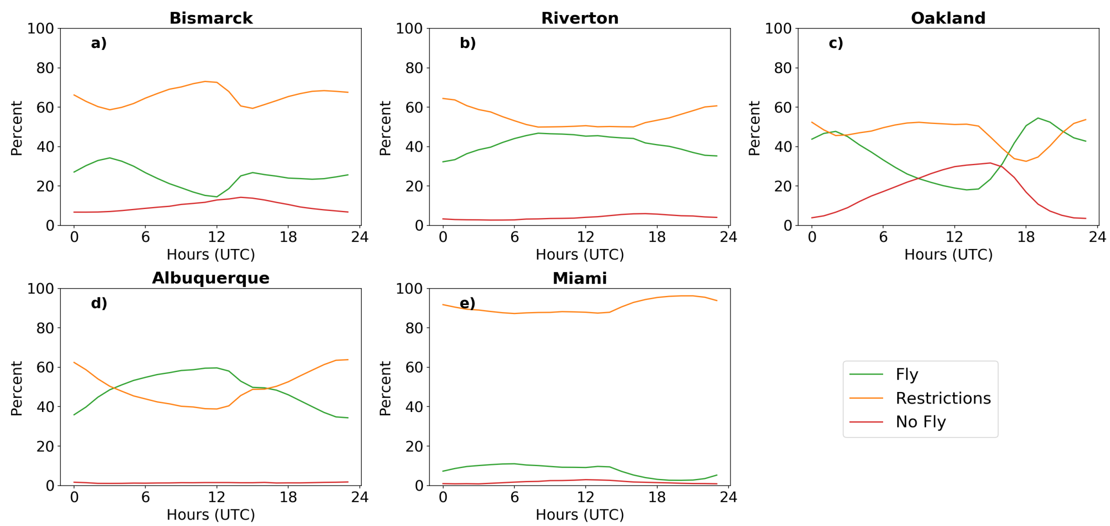

Figure 4: Percentage of time UA can operate (green), operate under restrictions (orange), or cannot operate (red) at each hour throughout the day for a) Bismarck, b) Riverton, c) Oakland, d) Albuquerque, and e) Miami.

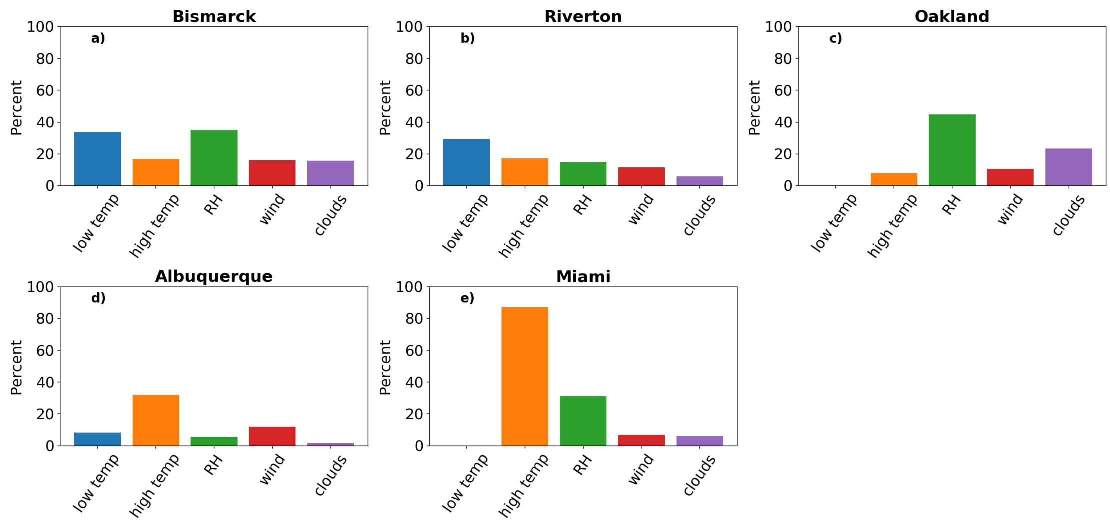

Figure 5: Percentage of time UA have restrictions or cannot operate due to low temperatures (blue), high temperatures (orange), high relative humidity (green), strong winds (red), or low cloud bases (purple) for a) Bismarck, b) Riverton, c) Oakland, d) Albuquerque, and e) Miami.

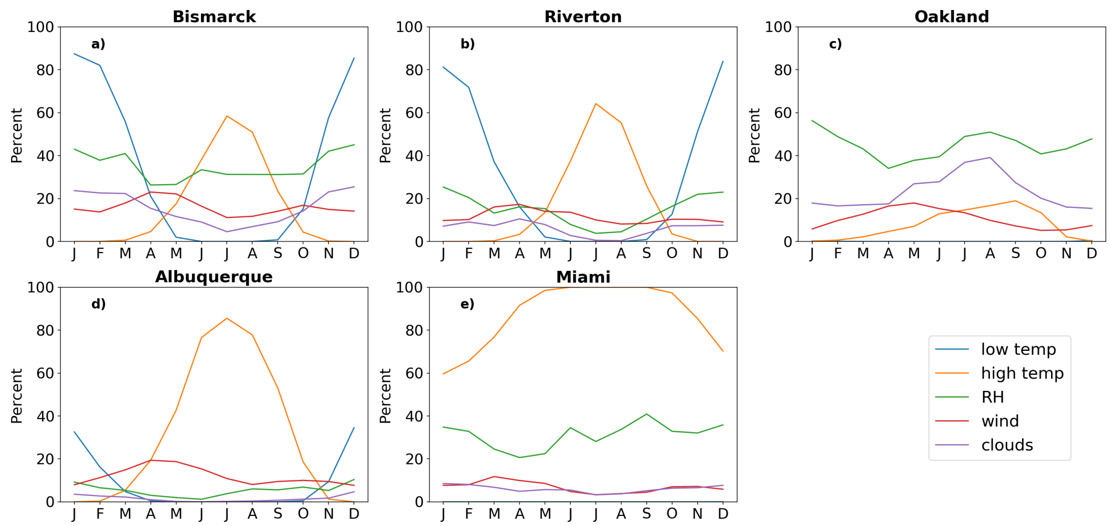

Figure 6: Percentage of time UA have restrictions or cannot operate throughout each month due to low temperatures (blue), high temperatures (orange), high relative humidity (green), strong winds (red), or low cloud bases (purple) for a) Bismarck, b) Riverton, c) Oakland, d) Albuquerque, and e) Miami.

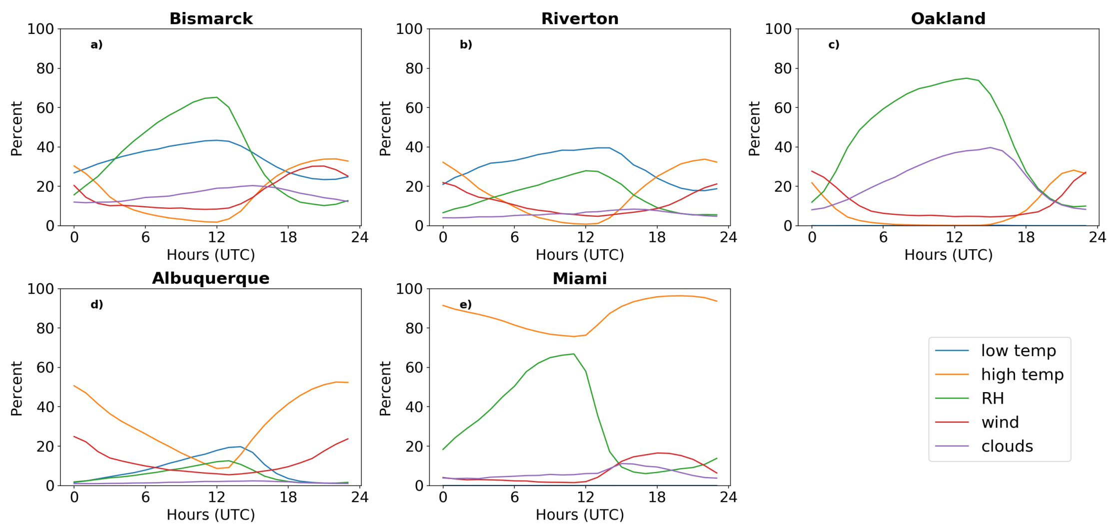

Figure 7: Percentage of time UA have restrictions or cannot operate at each hour of the day due to low temperatures (blue), high temperatures (orange), high relative humidity (green), strong winds (red), or low cloud bases (purple) for a) Bismarck, b) Riverton, c) Oakland, d) Albuquerque, and e) Miami.

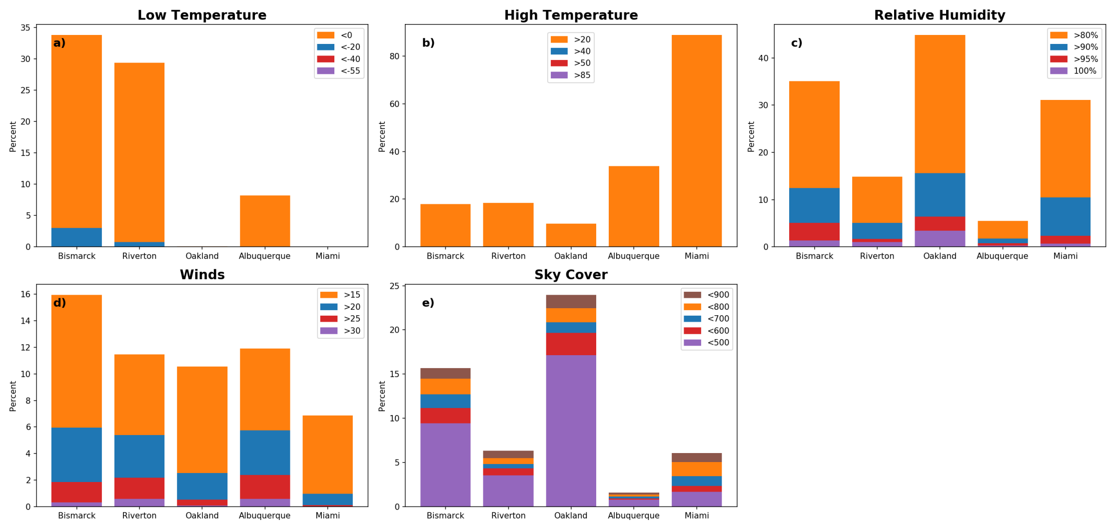

Figure 8: Overlaid bar chart of the time UA have restrictions or cannot operate at Bismarck, Riverton, Oakland, Albuquerque, and Miami broken down by the thresholds met for a) low temperature, b) high temperature, c) relative humidity, d) wind, and e) sky cover. (Note: The bars are overlaid, not stacked, and the percentages vary between each panel.)

5.2 Sounding Data

Soundings are analyzed at Bismarck, Riverton, Oakland, Albuquerque, and Miami with sample sizes of 22707, 22308, 22550, 22634, and 17175, respectively, across a 30-year period starting in 1988. The amount of time UA can operate, operate under restrictions, or cannot operate is broken down across 00 UTC and 12 UTC sounding launches and shown in Figure 9. Bismarck, Riverton, and Miami have a similar percent of limitations in the morning and in the afternoon. The amount of time UA can operate without restrictions in Bismarck increases by 4.6%, to 23.4%, from 12 UTC to 00 UTC, indicating that afternoon flights would face fewer restrictions (Fig. 9a). The opposite is true for Riverton and Miami, where the amount of time UA operate without restrictions decreases from 12 UTC to 00 UTC by 8.6% and 0.7%, respectively. Although the amount of times containing restrictions doubles from the afternoon to the morning in Miami, the percent of time UA cannot operate at all stays relatively similar with 3.0% and 1.0% at 12 UTC and 00 UTC, respectively. Oakland has the largest change in percent of time UA operate without restrictions, from 29.5% at 12 UTC to 59.5% at 00 UTC, indicating UA are half as likely to fly without restrictions in the morning compared to the afternoon (Fig. 9c). The percent of time UA operate without restrictions decreases almost 20% from 12 UTC to 00 UTC in Albuquerque, with most of that becoming restrictions; however, the percent of time UA cannot fly more than doubles from 2.0% to 4.4% in that same time.

To further investigate what is contributing to restrictions and to utilize vertical information included with sounding observations, the percent of time UA can operate, operate under restrictions, or cannot operate are shown at 100 ft intervals, up to 1000 ft AGL, along with the percentage of time each parameter individually reaches the thresholds set for grounding or restrictions. Starting with Bismarck, Fig. 10a shows an increase in the percent of time a UA cannot operate as a function of height. From 400 ft to 600 ft, the percentage of time a UA cannot operate increases from 2.7% to 6.6%, and continues to increase to 16.5% at 1000 ft. Relative humidity has the highest percentage of restrictions at the surface and decreases from 43.4% to 28.1% at 100 ft, remaining fairly consistent above 100 ft (Fig. 10b). The restrictions due to temperature are consistent with height; however, the restrictions due to high wind speeds increases significantly with height. At the surface, winds only cause restrictions or grounding ~15% of the time, whereas at 1000 ft the restriction rate is 63.8%.

The meteorological parameters that cause either UA restrictions or times where a UA cannot be flown are characterized by the percentage of time the thresholds for each meteorological parameter are met for 00 UTC and 12 UTC soundings. For Bismarck, the restrictions due to low temperatures stay relatively consistent with height, but have a slight increase in restrictions at 00 UTC and a slight decrease at 12 UTC (Figs. 11a,b). At the surface, restrictions due to low temperatures almost double from 23.4% at 00 UTC to 40.9% at 12 UTC. Similarly, restrictions due to high temperatures are relatively constant with height; however, high temperatures cause restrictions almost 25% more often at 00 UTC than at 12 UTC (Figs. 11c,d). Relative humidity causes the majority of the restrictions at the surface (Fig. 10b), and of those restrictions the highest impact is at 12 UTC when the restrictions reach 66.9% (Fig 11f). At 00 UTC, the restrictions due to high relative humidity values decrease from the surface to 100 ft and then increase up to 1000 ft to 17.9% (Fig 11e), where relative humidity values at 12 UTC are over 90% up to 20% of the time. Therefore, in Bismarck, relative humidity values limit UA operations more in the morning when the air temperatures are lower and closer to saturation than in the afternoon. The percent of time UA operations are limited due to high wind speeds increases with height for both the 00 UTC and 12 UTC soundings (Figs. 11g,h). At the surface, Bismarck has restrictions due to high wind speeds 12% more often at 00 UTC than 12 UTC. The afternoon soundings are typically more dry as the boundary layer becomes well mixed due to strong heating, so the parcels with high momentum aloft descend dry adiabatically down to the surface. Between 500 ft and 600 ft, the restrictions start to occur more frequently at 12 UTC than 00 UTC and continue up to 1000 ft where there are restrictions due to high wind speeds 63.4% and 55.7% of the time at 12 UTC and 00 UTC, respectively. Additionally, the wind speeds increase more rapidly with height at 12 UTC and are over 30 mph at 1000 ft almost twice as often than at 00 UTC. Overnight, the boundary layer becomes decoupled due to the nocturnal jet and the vertical mixing becomes minimal. Without vertical mixing, there is less drag from the lower levels of the atmosphere in the morning hours. The percentage of time UA flight is restricted due to high relative humidity in combination with the wind speeds increasing with height explains the decrease in flight restrictions from the surface to 100 ft, and the higher percentage of flight restrictions at higher elevations. Although the restrictions and grounding for UA operations in Bismarck are similar between 00 UTC and 12 UTC (Fig. 9a), the meteorological parameter that contributes to the restrictions varies. Wind speeds have similar restrictions for both 00 UTC and 12 UTC soundings, but low temperatures and relative humidity have the most restrictions at 12 UTC, and high temperatures have the most restrictions at 00 UTC.

A similar analysis is presented for Riverton and is shown in Figs. 12 and 13. The percentage of time UA cannot operate increases with height, up to 6.3% at 1000 ft. UA operate without any restrictions ~50% of the time in Riverton at all heights, which is 20-30% more frequently than in Bismarck (Fig. 12a), and both locations show similar patterns in meteorological parameters that cause the most restrictions (Fig. 12b). Low temperatures have the greatest impact on UA restrictions up to 400 ft, while relative humidity has the second greatest impact at the surface with restrictions 17.4% of the time and decreasing to 10.9% at 100 ft. Similar to Bismarck, restrictions due to high wind speeds increase significantly with height. Winds become the highest contributing factor to UA restrictions at 400 ft with restrictions 24.9% of the time, and increasing up to 31.0% of the time at 1000 ft.

Restrictions due to low temperatures in Riverton stay relatively consistent with height above 300 ft, with ~10% increase in restrictions with height at 00 UTC and a similar decrease at 12 UTC (Figs. 13a,b). Low temperatures limit UA operations just over 20% of the time at 00 UTC and above 30% of the time at 12 UTC, and the temperatures only drop below -20°C in the 12 UTC soundings. The high temperature restrictions follow a similar pattern as Bismarck, wherein the percent of the time UA have restrictions is consistent with height (Figs. 13c,d), with a slight increase in restrictions around 300 ft at 00 UTC. Restrictions due to high temperatures reach up to 27.1% at 300 ft at 00 UTC, which is more than 20% more often than at 12 UTC. Relative humidity accounts for a large percentage of restrictions at the surface, which primarily occurs during the 12 UTC soundings (Fig. 13f), similarly to Bismarck. At the surface at 12 UTC, relative humidity values are greater than 80%, 24.7% of the time, whereas at 00 UTC restrictions only occur 5.4% of the time (Fig. 13e,f). The 00 UTC soundings have a very minimal change in restrictions with height, and reach relative humidity values over 80% only about 5% of the time at all heights, whereas the relative humidity values at 12 UTC are above 90% about 5% of the time. The restrictions due to high wind speeds increase with height with both the 00 UTC and 12 UTC soundings, however the percentage of restrictions at 00 UTC goes from 20.6% at the surface up to 31.1% at 1000 ft and starts much lower at 12 UTC, from 5.9% at the surface to 28.2% at 1000 ft (Figs. 13g,h). The 00 UTC soundings have a higher percentage of time with winds above 20 mph than the 12 UTC at all heights, but the wind speeds exceeding 25 mph and 30 mph are similar at both times at 1000 ft, reaching ~11% and ~6%, respectively. Wind speeds have the greatest influence on restrictions in Riverton and explain the higher percentage of flight restrictions at higher altitudes. The increase in restrictions and grounding at 00 UTC (Fig. 9b) are primarily due to wind restrictions near the surface at 00 UTC.

For Oakland, restrictions occur 57.6% of the time at the surface, and then drop to only 48.9% of the time at 100 ft before slowly increasing again with height (Fig. 14a). Relative humidity produces the highest percentage of restrictions at all heights in Oakland. At the surface, high relative humidity causes restrictions 50.8% of the time, and then decreases to ~40% of the time at all other heights, which directly follows the pattern of the combined UA restrictions in Oakland (Fig. 14b). The restrictions due to high temperature stays fairly consistent at all heights, and restrictions due to high wind speeds increases with height from 3.2% at the surface to 18.1% at 1000 ft.

No restrictions due to low temperature occur in Oakland (Figs. 15a,b). Restrictions due to high temperatures stay relatively consistent with height (Figs. 15c,d), however the 00 UTC soundings have a higher percentage of restrictions than the 12 UTC soundings, with restrictions at the surface of 23.9% compared to <1% in the morning. Restrictions due to high temperatures decrease with height at 00 UTC, but still are more than 10% higher than the restrictions at 12 UTC. High relative humidity values produce the most restrictions for the 12 UTC soundings, with the highest percentage of restrictions at the surface at 79.8%, and decreasing to only 63.1% at 100 ft (Fig. 15f). Figure 15e shows an increase in the percentage of restrictions due to high relative humidity values with height at 00 UTC, reaching 20.1% at 1000 ft. The restrictions due to relative humidity values over 80% at 00 UTC are comparable to the restrictions for relative humidity values over 95% at 12 UTC, indicating a much higher frequency of limitations and grounding due to high relative humidity values in the morning than in the afternoon. Wind speeds in Oakland have limited restriction impacts, but both the 00 UTC and 12 UTC soundings experience an increase in restrictions with height (Figs. 15g,h). Slightly more restrictions occur with the 00 UTC soundings as compared to the 12 UTC soundings, with an average of a 5.2% increase in restrictions in the afternoon; however, restrictions do not reach above 20% at any height and the wind speeds are only above 20 mph ~5% of the time at 1000 ft. With relative humidity as the primary restriction in Oakland, the percentage of time UA can be flown will increase in the afternoon (cf. Fig. 9c).

Albuquerque has restrictions at all heights ~50% of the time, with a slight increase in restrictions up to 56.3% at 1000 ft (Fig. 16a). The percentage of time a UA cannot operate increases by ~4% from the surface to 1000 ft. High temperatures have the highest impact on restrictions up to 700 ft, with restrictions to UA operations 29.9% of the time at the surface and staying fairly consistent at all heights (Fig. 16b). The percentage of time high wind speeds cause restrictions increases with height to 34.9% of the time at 1000 ft, becoming the most impactful meteorological parameter above 700 ft.

Low temperatures cause restrictions to UA operations primarily below 200 ft at 12 UTC, with restrictions less than 5% of the time at all heights during the 00 UTC soundings (Figs. 17a,b). Above 200 ft at 12 UTC, restrictions due to low temperatures are consistently around 10%. Figures 17c,d show the percentage of time UA operations are restricted due to high temperatures, with the greatest impact at 00 UTC. Restrictions due to high temperatures increase up to 47.2% at 300 ft at 00 UTC and then slowly decrease to 40.6% at 1000 ft, which accounts for the majority of the time UA are restricted. Relative humidity values have very little impact on UA operations in Albuquerque (Figs. 17e,f), with restrictions occurring only ~1% and

~6% of the time at all heights at 00 UTC and 12 UTC, respectively. Wind speeds are one of the primary factors for restrictions to UA operations (Fig. 16b), and it is apparent that restrictions due to high winds increase significantly with height. The 00 UTC soundings have 14.7% more restrictions than the 12 UTC soundings at the surface; however, the percentage of time UA have restrictions increases more rapidly with the 12 UTC soundings than with the 00 UTC soundings (Figs. 17g,h). At 1000 ft, the 00 UTC soundings have restrictions 32.9% of the time, whereas the 12 UTC sounding increases up to 27.9% at 1000 ft. Wind speeds are typically higher at 00 UTC with wind speeds reaching over 30 mph over 6% of the time at 1000 ft and only 3.7% of the time at 12 UTC. The percentage of time UA are restricted due to high temperatures at 00 UTC, in combination with a slight increase in restrictions with height due to wind speed, explains the relatively consistent amount of restrictions with height in Fig. 16a. In addition, due to the significantly higher percentage of restrictions due to high temperatures at 00 UTC and wind speeds closer to the surface being higher at 00 UTC, the percentage of time UA can operate at 00 UTC is less frequent than at 12 UTC (Fig. 9d).

Similar to Albuquerque, UA restrictions at Miami are fairly consistent with height, but occur ~90% of the time (Fig. 18a). The percentage of time a UA cannot be operated decreases from 1.9% at the surface to 0.8% at 100 ft and then increases above 100 ft. Restrictions due to high temperatures occur over 80% of the time at all heights, with the high relative humidity having the second greatest impact at most levels (Fig. 18b). The percentage of restrictions due to wind speeds increases with height from 1.4% at the surface to 47.9% at 1000 ft.

Low temperatures do not account for any restrictions to UA operations in Miami (Figs. 19a,b). Restrictions due to high temperatures are fairly consistent with height, reaching up to 90% for both 00 UTC and 12 UTC soundings (Figs.

19c,d). Temperatures do not reach above 40°C at any time, so flight operations are not disallowed because of high ambient temperatures. As stated in §4.3, the components may emit higher temperatures and increase the aircraft temperature to above operating limits. Relative humidity values produce the most restrictions at the surface for the 12 UTC soundings, with restrictions 81.4% of the time that decrease with height to ~65% of the time (Figs. 19e,f). Relative humidity is at 100% at 12 UTC ~2% of the time at all heights, whereas at 00 UTC the relative humidity does exceed 95% more than 0.5% of the time. Miami has similar wind speeds at 00 UTC and 12 UTC (Figs. 19g,h), with both sets of soundings showing an increase in restrictions with height from ~1% at the surface up to 39.1% and 44.4% at 00 UTC and 12 UTC, respectively. Wind speeds exceed 30 mph primarily above 600 ft, which would completely ground all small UA operations above those heights, up to 3% of the time. Wind speed restrictions account for the increase in time a UA cannot operate at higher altitudes. High temperatures account for the majority of the restrictions in Miami, and are similar between the 00 UTC and 12 UTC soundings. However, the higher relative humidity values at 12 UTC explain the 2% increase in grounding for UA operations.

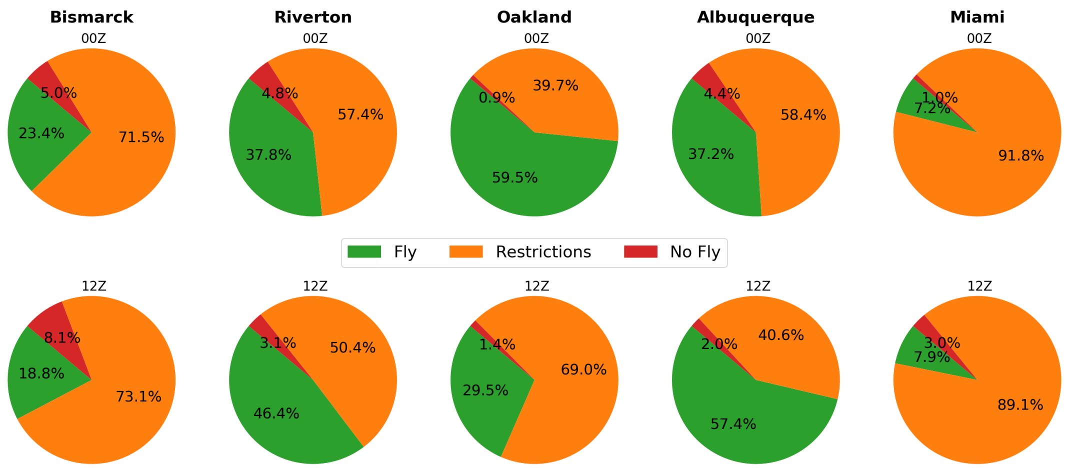

Figure 9: Percentage of time UA can operate (green), can operate under restrictions (orange), or cannot operate (red) combining all heights all 00 UTC (top) and 12 UTC (bottom) soundings for a) Bismarck, b) Riverton, c) Oakland, d) Albuquerque, and e) Miami.

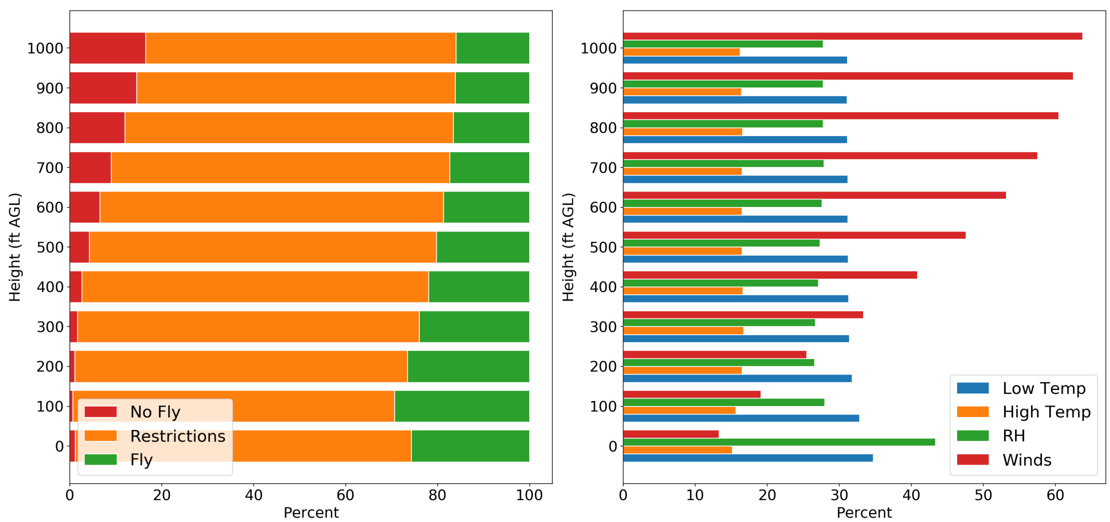

Figure 10: Interpolated sounding data for Bismarck in 100 ft increments from the surface to 1000 ft AGL showing the a) percentage of times UA can operate (green), can operate with restrictions (orange), or cannot operate (red) based on all meteorological parameters and b) percentage of impact from individual meteorological parameters that restrict or ground UA operations at each height.

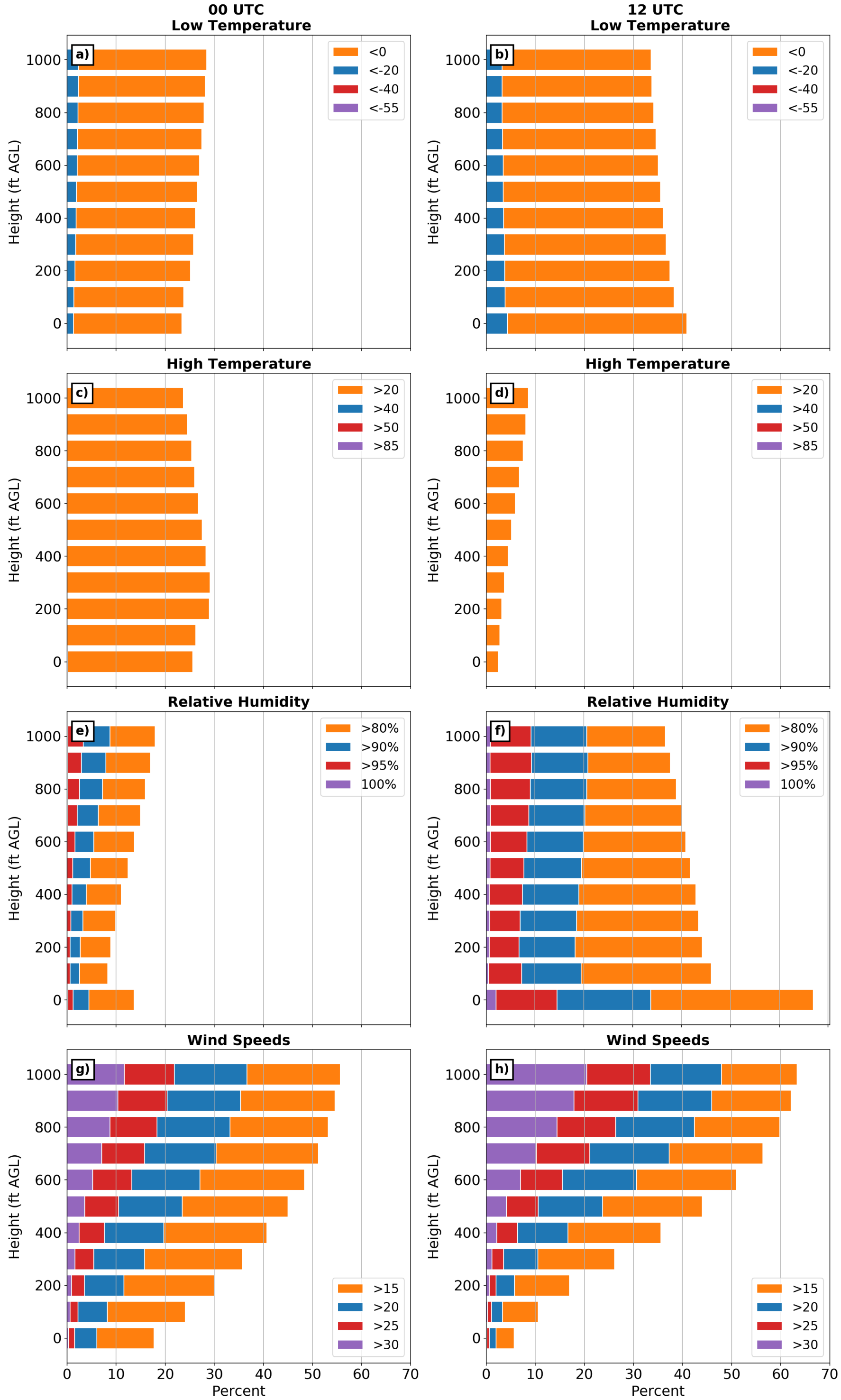

Figure 11: The percentage of time each meteorological parameter threshold is breached resulting in UA flight restriction or grounding with height for 00 UTC (left; a, c, e, g) and 12 UTC (right; b, d, f, h) sounding data for a,b) low temperatures, c,d) high temperatures, e,f) high relative humidity, and g,h) strong wind speeds.

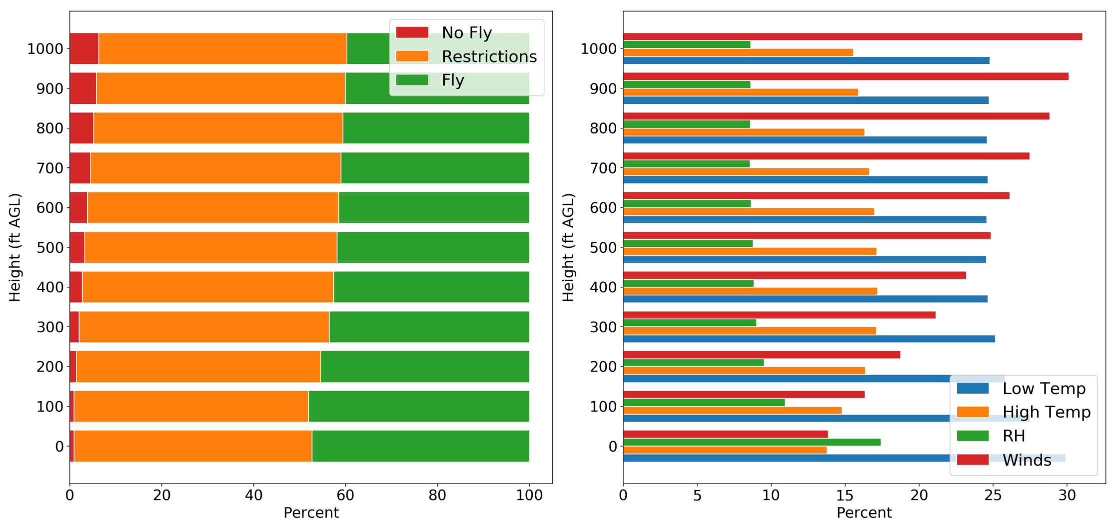

Figure 12: As in Figure 10, except for Riverton.

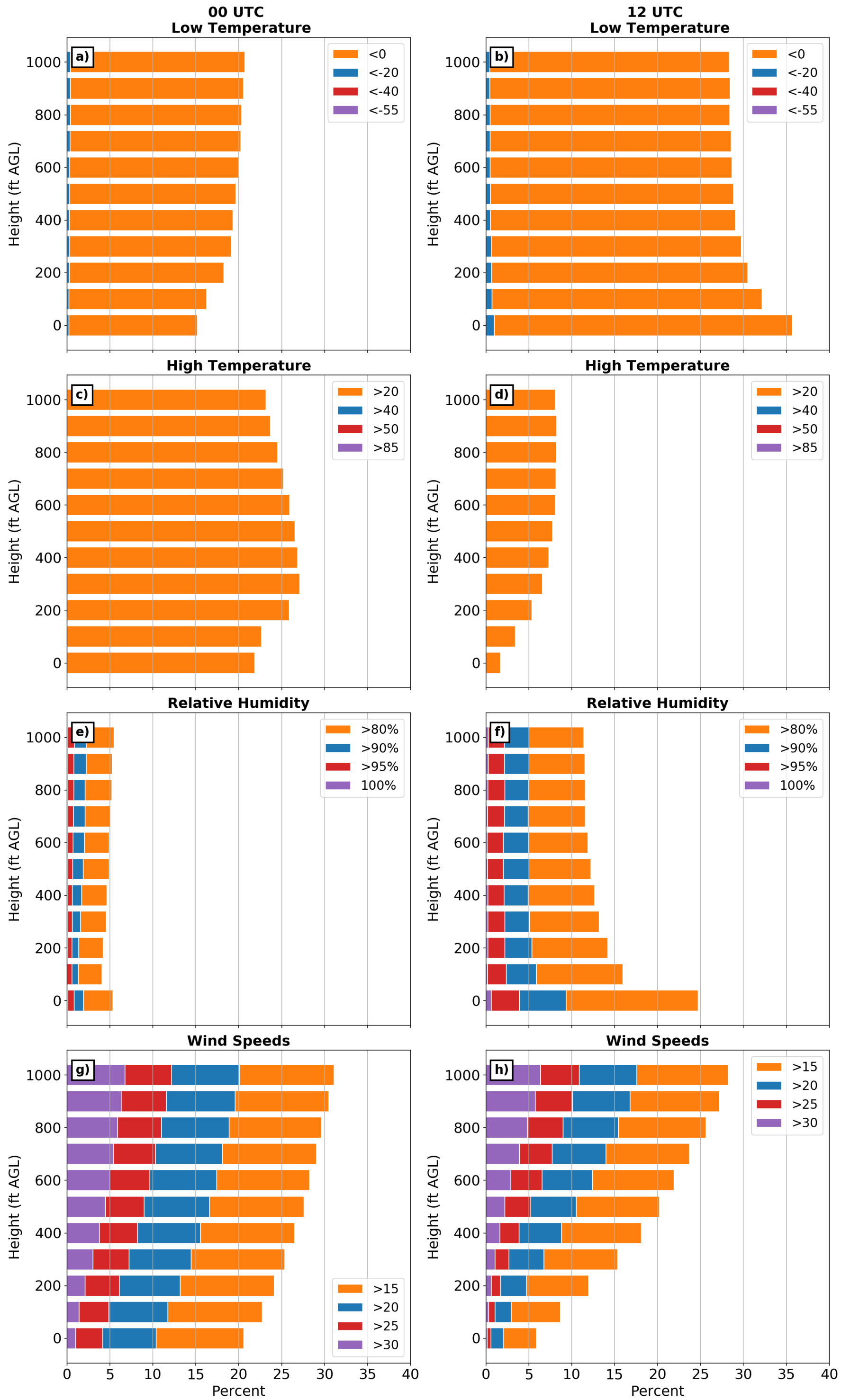

Figure 13: As in Figure 11, except for Riverton.

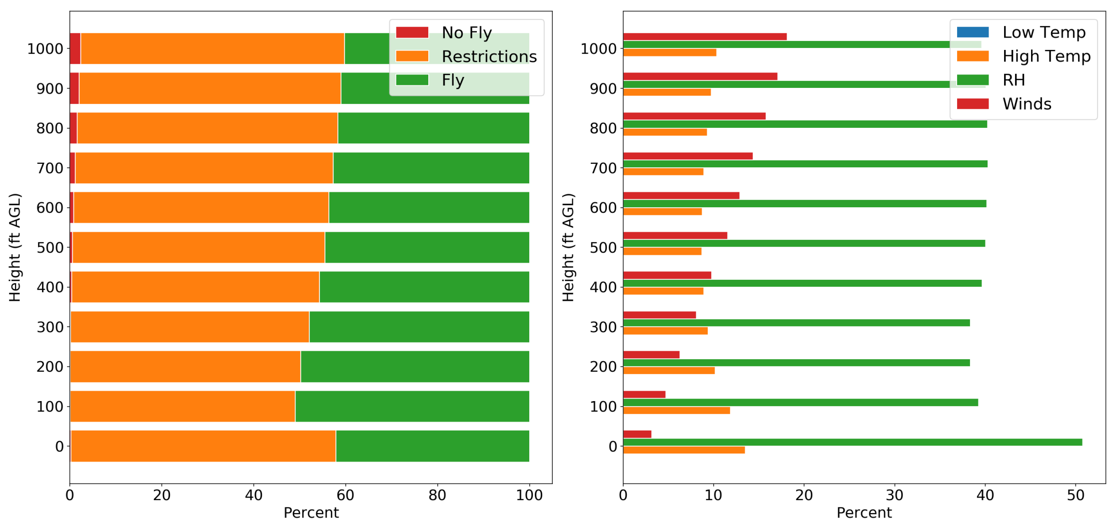

Figure 14: As in Figure 10, except for Oakland.

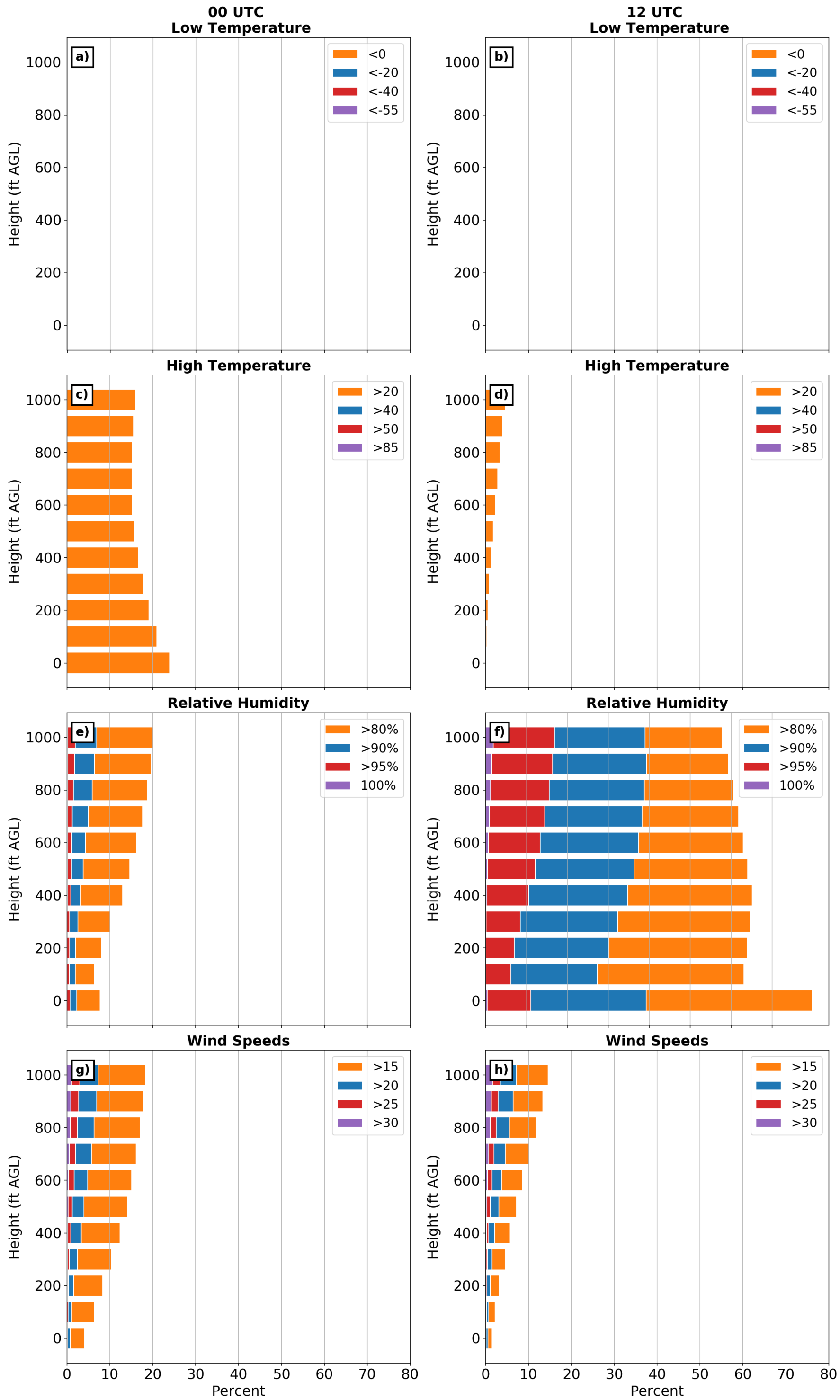

Figure 15: As in Figure 11, except for Oakland.

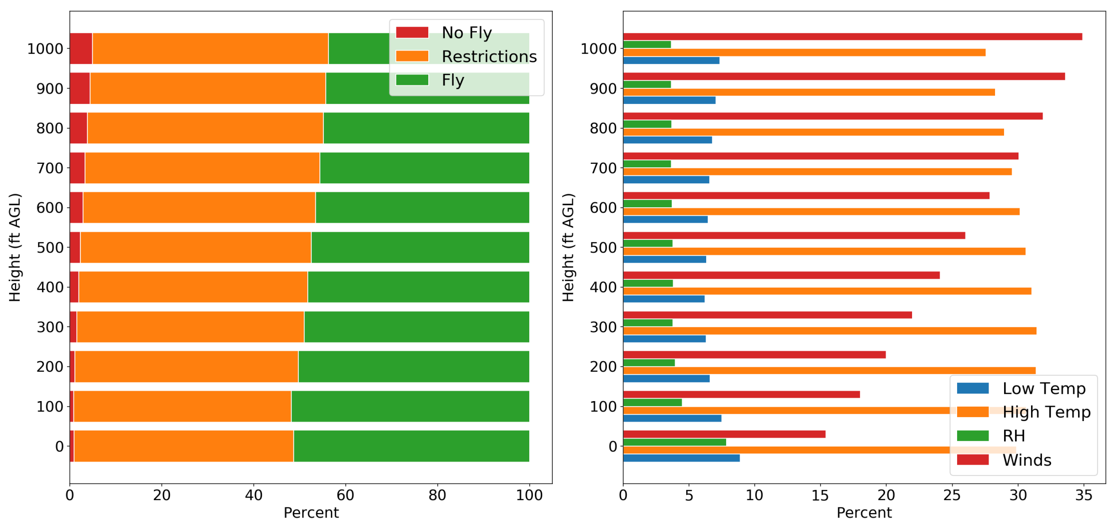

Figure 16: As in Figure 10, except for Albuquerque.

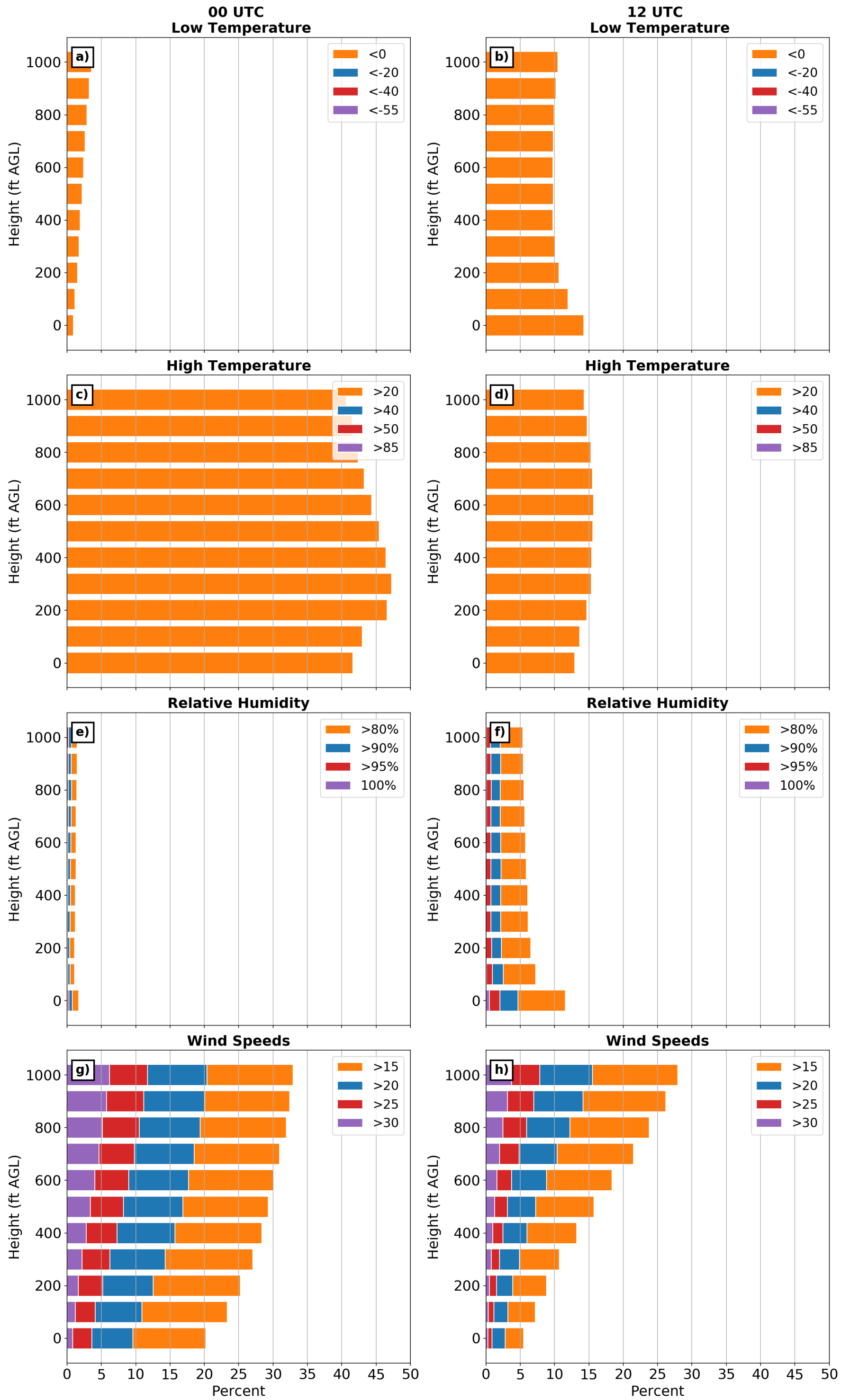

Figure 17: As in Figure 11, except for Albuquerque.

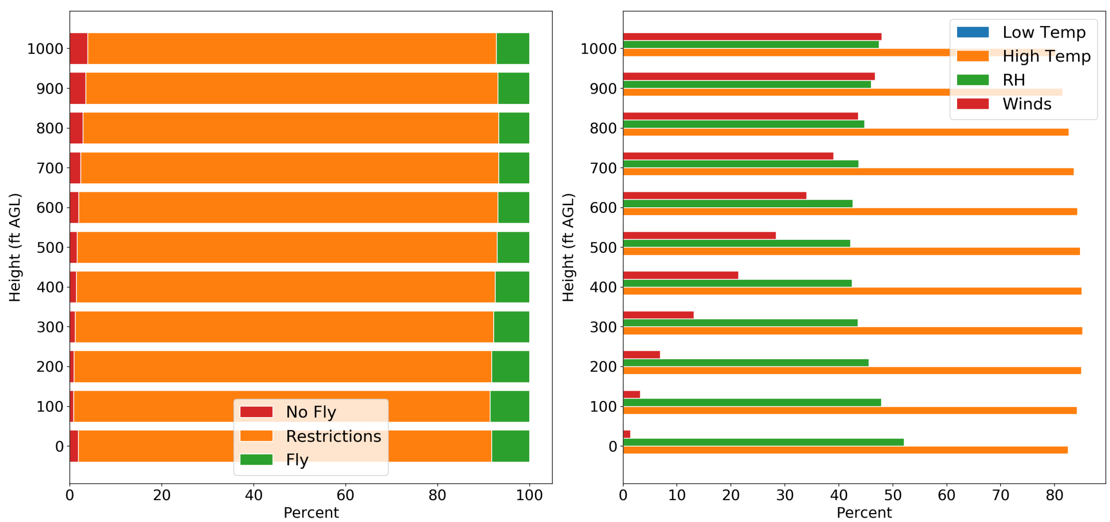

Figure 18: As in Figure 10, except for Miami.

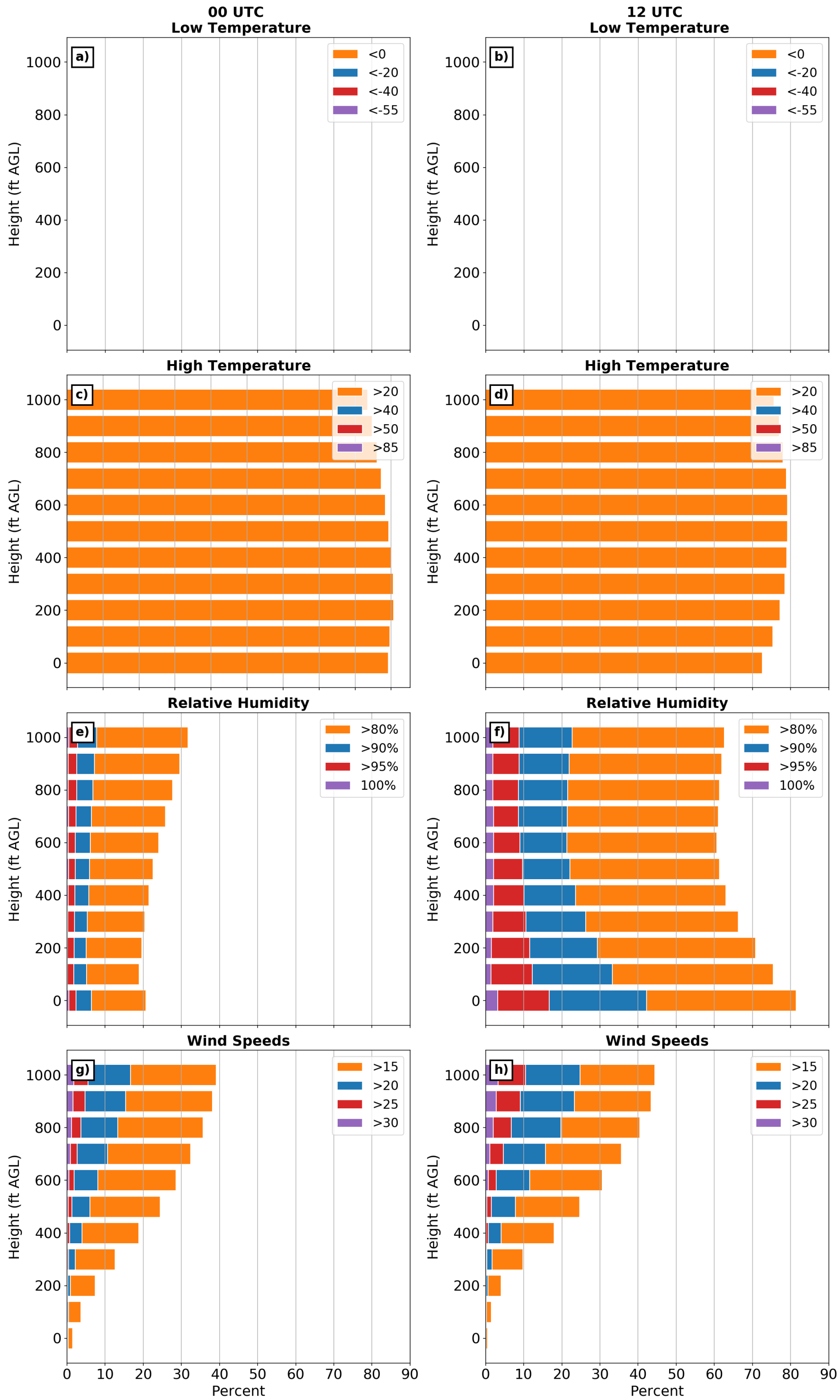

Figure 19: As in Figure 11, except for Miami.

CHAPTER 6

DISCUSSION

6.1 Implications of Results

The results from the 30-year climatology show that the meteorological parameters most impactful to UA flight vary by location. They also show that flight restrictions at each location are impacted by seasonal and diurnal variations. These results are used to understand meteorological impacts that are observed in a climatological area that can be translated to other, climatologically-similar regions.

Restrictions due to reaching temperature thresholds do not noticeably change with elevation, and are consistent throughout the diurnal cycle with generally higher temperatures in the afternoon and lower temperatures in the morning. However, seasonal variations are significant. Low temperatures cause the highest percentage of flight restrictions in Bismarck and Riverton, and reach values as low as -20°C – primarily during the winter months. Following the Köppen-Geiger climate map (Kottek 2006), both of these locations are represented by climates with snow, indicating that in such regions one must utilize UA that are equipped for flight in temperatures below -20°C; otherwise, UA are generally restricted to flights from March through November. These regions, along with Albuquerque, are considered arid, and experience additional extreme temperatures during the summer months. Albuquerque is most impacted by high temperatures, but would require UA that can be operated in both colder and warmer climates along with much of the southwest United States. High temperatures do not reach above 40°C at any location and are typically the greatest during the summer months in warm temperate regions, such as the south, southeast, and much of the Ohio River Valley. UA that are equipped to operate in temperatures up to 40°C should be used in warmer climates, such as Miami and Albuquerque.

Oakland, followed by Bismarck and Miami, has the most restrictions due to high relative humidity values and each are considered 'fully humid' (Kottek 2006). Restrictions due to high relative humidity do not change significantly throughout the year, but diurnal variations do occur as daytime shortwave heating ends and the atmosphere cools to saturation. If a UA cannot be operated in relative humidity values above 80%, the best time for UA flight operations, particularly along much of the western coast, is in the afternoon when UA operation restrictions are minimally affected by relative humidity. Additionally, in Oakland, the relative humidity reaches 100% and cloud bases are below 500 ft a significant fraction of time, so in order to operate UA in a warm, humid climate during the morning hours UA must be equipped to fly in 100% relative humidity and waivers to fly UA with low cloud bases present must be obtained.

High wind speeds produce the greatest number of restrictions by location in Bismarck, with similar percentages of restrictions in Riverton and Albuquerque. Wind speed restrictions are constant throughout the year but follow diurnal-cycle-driven changes. As the boundary layer becomes well mixed due to strong heating in the afternoon, wind speeds start to increase, resulting in more flight restrictions due to winds after 18 UTC. Wind speeds are not a primary limitation to UA operation in these five locations, however the wind speeds are above 25 mph a significant fraction of the time in arid climates, so in order to fly UA in the afternoon one must be able to fly UA in wind speeds above 25 mph to reduce restrictions. Also, winds result in more restrictions at higher altitudes at all locations, indicating that an aircraft that can be flown with stronger winds is needed for flights at higher altitudes.

6.2 Respresentativeness of Wind Data

Evaluation of wind speeds in §5.1 uses the reported surface winds, which are the 2-minute mean wind speeds; however, this does not account for wind gusts that may be notably greater than the sustained wind speed. If the wind exceeds the mean wind speed by over 10 knots, a wind gust value is provided. To evaluate the impact wind gusts have on restrictions for small UA, restrictions and grounding based on sustained wind speed and wind gusts at the surface are compared only on days when wind gusts are reported (Fig. 20). For all of the locations, every time there is a wind gust, it is over 15 mph. When utilizing wind gust data instead of sustained winds, a UA is ~30% more likely to have flight restrictions in Bismarck, Riverton, Oakland, and Albuquerque, and 69.1% more likely to have restrictions in Miami. In addition, the wind gusts over 30 mph occur six to eight times more frequently than sustained winds over 30 mph, indicating that although UA may be flown under restriction with sustained winds, they would be grounded using wind gusts. It is important to note that these data are biased towards high sustained winds, as the times that have reported wind gusts generally have higher wind speeds.

Instead of restricting the wind data to only times when wind gusts were reported, Fig. 21 shows the frequency with which sustained winds reach the defined thresholds compared to the frequency with which wind gusts are reported and reach the defined thresholds. If a wind gust is not reported, the data for that time is recorded with a wind gust of 0 mph and the wind speed assigned the reported value. Bismarck has the highest percentage of restrictions due to wind gusts at all times with restrictions 12%, followed by Albuquerque with restrictions 11% of the time.

Although there are slightly less restrictions due to wind gusts in Albuquerque than Bismarck, the frequency of wind gusts that cause restriction or grounding is nearly as high as that for sustained wind speed, indicating that wind gusts are reported almost as often as the wind speeds are reported over 15 mph. Miami has more wind-gust-based restrictions than sustained wind speed restrictions. In Bismarck, Riverton, and Albuquerque, wind gusts are reported above 30 mph, grounding all UA flight ~3.5% of the time, which is over 2% more frequently than sustained wind speeds. Oakland only reports wind gusts that cause restrictions 2% of the time. These results show that wind gust cannot be ignored. Many cases occur where the sustained wind speeds indicate safe UA operations or restrictions for wind speeds up to 15 mph when the wind gusts are at or above 30 mph and will ground all small UA.

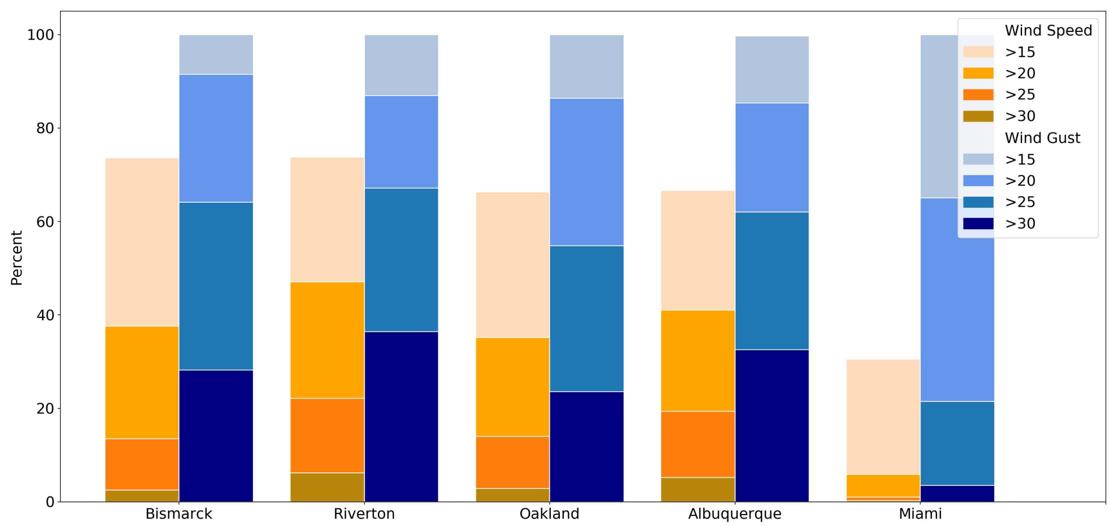

Figure 20: Percentage of time the wind speeds (orange) and wind gusts (blue) reach thresholds resulting in UA flight restriction or grounding on days when wind gusts are reported for each location.

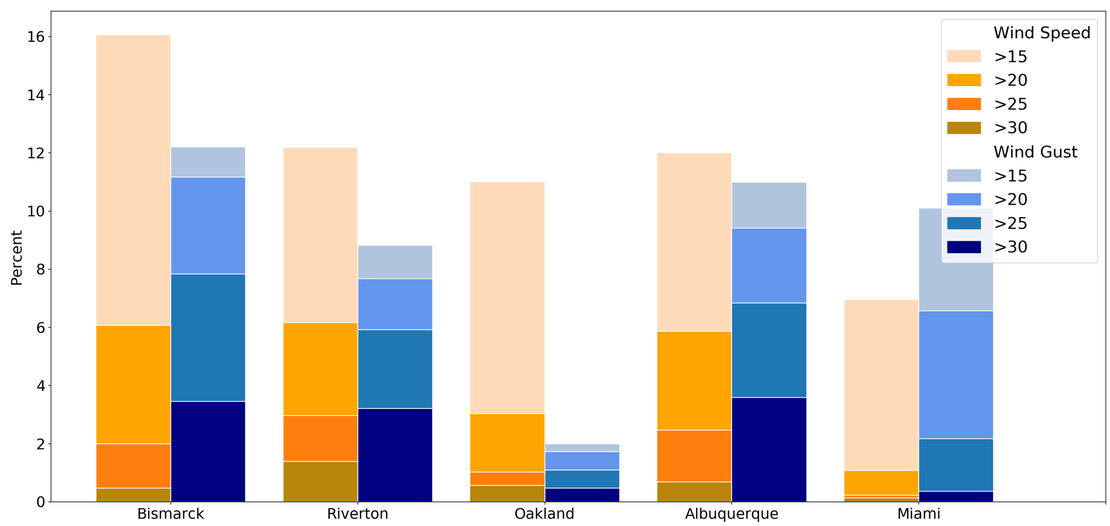

Figure 21: As in Figure 20, except for all days (whether or not gusts were reported).

6.3 Comparison of Surface Data

To determine if the results from the surface data and the sounding data are comparable, surface and sounding data are filtered to times where data are provided for each type and compared in Fig. 22. Total percentage of times when UA have restrictions or are grounded at each location have less than 3% variation between surface and sounding data, with the largest spread in Riverton, followed by Miami at 2.8% and 2.4%, respectively (Fig. 22b,e). The largest variation in percentage of restrictions and grounding is most commonly due to high relative humidity and strong winds.

There is less than a 5% difference between surface and sounding data owing to reaching temperature thresholds (Fig. 22). Restrictions due to low temperatures occur more frequently at surface stations than with the sounding data, and the opposite is true for high temperatures, indicating that the surface stations generally provide lower temperature readings than the soundings.

Relative humidity causes restrictions or grounding in Miami 36.2% of the time from the surface stations and 51.4% of the time by utilizing the relative humidity data from the soundings (Fig. 22e). The significant increase in restrictions from the surface data to the sounding data is observed at almost all locations. It is noted in FMH3 (Baker et. al. 1997, §4.4) that it is not uncommon for sounding-based relative humidity values at the surface to have error. The error typically occurs when a radiosonde is calibrated in a room with different temperature and relative humidity values than the release point and the sensors are not being properly ventilated prior to release. Additionally, the instruments used to measure moisture content are not the same for surface data and sounding data. Surface data are collected from a height of 2 m, and the instrument varies according to the system in use at a particular location (OFCM 2019). The data are reported to the nearest whole degree Celsius, and can contain uncertainties up to 2°C utilizing the dew point probe that is enclosed in a radiation shield within an open structure. A hygristor is utilized to measure moisture using radiosondes and is placed at a location where outside air passes over the instrument package (Hopkins 1996). The hygristor consists of a plastic or glass slide covered with a moisture sensitive film of lithium chloride that produces chemical changes with changes in atmospheric humidity. Lastly, the data from a sounding starts at an altitude of $<$1 m or from the observer's hand, whereas the surface data are observed at an altitude of 2 m, which results in slight variations of the observations.

The percentage of restrictions due to high wind speeds has the most variation between surface and sounding data at Bismarck, Oakland, and Albuquerque, with Oakland being the highest at 12.1% (Fig 22a,c,d). Discussion of anomalies with wind data near the surface is provided in Baker et. al. (1997, §4.5.3.2), noting that data containing rapid wind speed changes near the surface may provide faulty data within the soundings and the error of the sounding data at the surface would be larger.

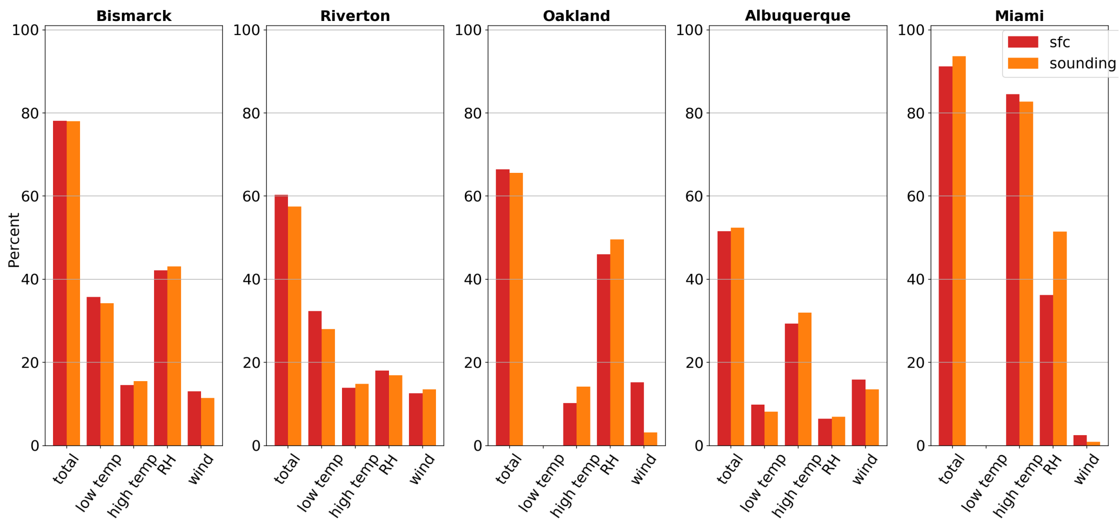

Figure 22: Percentage of time UA have restrictions or grounding from surface data (red) and sounding data at the surface (orange) for all times where both datasets are available for a) Bismarck, b) Riverton, c) Oakland, d) Albuquerque, and e) Miami. The first column has the total percentage of time removing all overlap from the meteorological parameters, and columns 2-5 have the impacts from low temperature, high temperature, relative humidity (RH), and wind.

6.4 Limitations

Several limitations are inherent to the data and methodology that limit the results of this study. First, five different locations are chosen to represent different environments in which UA may be operated. These locations do not capture all of the complex weather and terrain impacts that may be present in the region they represent. Temperatures can change over a short distance based on elevation, urban areas, and surrounding features (i.e. lakes and oceans, precipitation, cloud cover) which would affect the impact of temperature on UA operations. Additionally, at the surface the winds are evaluated at airports, which provide minimal turbulence and wake effect. UA operate in (or will be operated in) large cities, and thus will encounter turbulence driven by structures (e.g., buildings) that will impact flight in addition to wind tunneling effects between buildings.

Although each of these locations are selected to be evaluated due to the likelihood of reaching a particular meteorological threshold, this study does not combine multiple parameters which could provide a change in operational timeframes. The thresholds for high temperature are not combined with the effects of cloud coverage, moisture, or heating from components inside the aircraft. Temperatures did not reach above 40°C in this study, however, a dark color (low albedo) aircraft (in combination with certain materials) will absorb energy from the sun and can overheat even though the ambient temperature does not reach the thresholds for the high temperatures. An increased moisture content in the atmosphere can cause condensation on components if they are not properly sealed and can result in failure if they are not designed to get wet. Similarly, condensation will freeze if low-enough temperatures are reached, which will cause rim icing on the exterior of an aircraft and component failures within the UA.

The analysis of the data underlie additional limitations to the results of this study. Sounding data are restricted in vertical resolution, being available at the standard pressure levels and significant levels, determined based on changes in the environment. During the interpolation of the sounding data, linear interpolation is assumed. Soundings that provide limited data are interpolated regardless of missing or fewer data points available, which can reduce the impact of certain meteorological parameters and result in limited resolution. Also, while interpreting the data, no rounding is done to evaluate the frequency of limitations (i.e. temperatures at 19.8°C would not be round up to 20°C where restrictions would apply). Uncertainties associated with individual observations are not considered. The temperature data provided by the surface stations are from a height of 2 m and have an error of up to 1.1°C (OFCM 2019), and sounding-based surface temperatures are from <1 m above the surface and have an accuracy of 0.4°C. The surface station dew point has an accuracy of ~1.5°C, which is then combined with temperature data to compute relative humidity. Sounding data have relative humidity errors of 2.5% if properly ventilated (Baker et. al. 1997). Wind data have an accuracy of up to 2 ms^{-1} for both surface and sounding data.

6.5 Future Work

This study does not include all meteorological impacts to small UA, nor does it encompass all locations in the Contiguous United States (CONUS). To gain a better understanding of the major meteorological impacts across the continent, more locations must be tested as well as a variety of other weather phenomenon. Based on FAA operational guidelines, UA cannot operate without waivers or permissions, while precipitation is present (Burns 2015), and the frequency with which this occurs is not evaluated herein. Additionally, precipitation in the surrounding area will impact visibility, winds, and temperature, so a separate study of precipitation alone is needed to fully understand these limitations. If water droplets are present in the air and temperatures are below 0°C, icing will occur on the aircraft which will increase potential LOC and reduce flight time. Icing is a major concern for UA as the PIC may not notice ice on the aircraft.

Turbulence can result in LOC, however is not evaluated herein due to the limited spatial and temporal resolution of the sounding data. Turbulence potential could be evaluated using sounding data, which can be used to compute the Richardson number. The Richardson number is the ratio of buoyancy to vertical wind shear, and indicates if turbulence can be sustained (Widseth 1999). If buoyancy is small in comparison to wind shear, turbulence can occur.

The impacts from convective thunderstorms are not discussed. However, thunderstorms produce numerous weather impacts for UA operations. Typically, precipitation, strong winds, lightning, possible hail and ice, low visibility, and other hazards to flying occur, which would restrict UA operations. In addition, under Part 107, the minimum visibility from the control station must be 3 statute miles or greater and UA cannot be flown outside of daylight hours or without VLOS, unless an appropriate waiver has been obtained, which is expected to reduce overall flight times (FAA 2018).

Last, a complete record of pilot weather reports (PIREPs) for UA would enable understanding of impacts of weather-related accidents. An understanding of what conditions are present and impacts to UA flight will increase knowledge of meteorological influences. It is expected that most PICs do not fill out accident reports, so knowledge of accidents or crashes is limited. For manned aircraft, pilots are asked to file PIREPs for every flight. However, Welferman (2017) noted that up to 81% of pilots do not submit reports. With this information, it can be inferred that many UA operators do not file PIREPs and additional weather information is not recorded.

CHAPTER 7

CONCLUSIONS

The purpose of this study is to estimate the frequency of potential weather-related restrictions for small UA, including the times at which they occur. In order to accomplish this goal, surface and sounding data are collected over a 30-year period at five locations across the continental United States and evaluated for the frequency of time temperature, moisture, wind, and cloud cover reach set thresholds that restrict or ground UA flight operations. The restrictions to UA flight at each location are used as a representation of the meteorological impacts that are observed in that area, which can be translated to other similar regions to understand the frequency of flight restrictions on UA operations.

The results show that the meteorological parameters most impactful to UA flight vary by location, season, and time of day; and, the type of UA that can be flown at each location is varied based upon the typical weather experienced. Flight restrictions in Bismarck are primarily from low temperatures in the winter months and high relative humidity values in the morning. Temperatures in Bismarck and the surrounding area reach as low as -20°C in the winter, so the UA must be equipped to be flown in similar temperatures or are restricted to flights primarily from March through October. Similarly, in Riverton low temperatures cause the greatest number of flight restrictions and occur during the winter months. In both areas, high temperatures cause some restrictions in the summer months, so UA that can be flown in temperatures above 20°C are required to alleviate those restrictions. High relative humidity values and low cloud bases are the most impactful meteorological parameters in Oakland and surrounding areas. Restrictions due to moisture occur primarily in the morning. Therefore, afternoon flights are less likely to have restrictions. For UA operations during the morning hours around Oakland, appropriate waivers (i.e., to Part 107) must be obtained to operate with low cloud bases and UA must be equipped to operate with significant moisture. Albuquerque has the most restrictions due to high temperatures, which occur primarily in the summer months. Winds cause the second highest percentage of restrictions in Albuquerque, with winds typically strongest in the afternoon. Wind speeds commonly reach above 25 mph around Albuquerque, so UA that operate in this area should typically fly in the morning and must be equipped to fly in strong winds for afternoon flights. High temperatures cause restrictions to UA flight in Miami and the surrounding area a significant portion of the year, but there is an increase in restrictions during the summer months. Temperatures do not reach above 40°C at any location, so not all UA are grounded owing to high temperatures. To fly UA around Miami and Albuquerque, however, one is enabled by being able to fly in temperatures up to 40°C.

In addition, sounding data are used to analyze meteorological parameters at altitudes above the surface. At all locations, wind speeds increase with height, resulting in the greatest number of restrictions at 1000 ft (the highest altitude at which analysis was performed). An aircraft that can be flown in stronger winds enables flights at higher elevations. Additionally, relative humidity values are highest at the surface and decrease rapidly up to 100 ft, which affects take-off and landing of UA. Temperature restrictions do not notably change with height, and above 100 ft the relative humidity values are relatively consistent.

To expand understanding of weather-related impacts on UA operations, an analysis of more geographic locations and meteorological parameters is needed. Impacts of precipitation, icing, and turbulence are not well known, and studies of these would further enable safe UA operations.

CHAPTER 8

REFERENCES

Adams, S. and Friedland, C., 2011: A Survey of Unmanned Aerial Vehicle (UAV) Usage for Imagery Collection in Disaster Research and Management.

Allianz, 2016: Rise of the Drones: Managing the Unique Risks Associated with Unmanned Aircraft Systems. *Allianz Global Corporate and Specialty.*

Askelson, M., 2002: Kinematic, Dynamic, and Thermodynamic Impacts of Hook-Echo Hydrometeors, including Explorations into the Utilization of Polarimetric Radar Data, Dissertation.

Askelson, M. and Coauthors, 2017: Small UAS Detect and Avoid Requirements Necessary for Limited Beyond Visual Line of Sight (BVLOS) Operations, A2 Final Report,*FAA*.

Baker, J. and Coauthors, 1997: Federal Meteorological Handbook No. 3: Rawinsonde and Pibal Observations.

Barkho, G., 2019: Google Launches First Drone Delivery Service in Australia, *Observer.*

Belcastro, C., Newman, R., Evans, J., Klyde, D., Barr, L., Ancel, E., 2017: Hazards Identification and Analysis for Unmanned Aircraft System Operations, *NASA*/docs.

Burns, J., 2015: Impact of Weather on and With UAVs. *Sensurion Aerospace Presentation.*

Calvetti, L., Toshio, R., Deppe, F., Beneti, C., 2012, High Resolution WRF Simulation for Wind Gust Events, *WMO/WWRP*.

Campbell, S., Clarck, D., and Evans, J., 2017: Preliminary Weather Information Gap Analysis for UAS Operations.

Chapman, A., 2016: Types of Drones: Multi-rotor vs Fixed-wing vs Single rotor vs Hybrid VTOL, *Drone Magazine*.

Clark, D., Ferris, R., and Moradi, D., 2018: Airport Wind Observations Architectural Analysis.

Cox, T. and Coauthors, 2006: Earth Observations and the Role of UAVs, Version 1.1.

Daly, K., 2018: The Future is Here: How Drones Are Modernizing the Healthcare Industry, Legal Issues Affecting Supply Chain, *Medical Alley*.

Elliot, C., 2013: Storm Warnings: How Do Airlines Know If It's Safe to Fly in Bad Weather? *National Geographic*.

English, W., 2017: Drone Operator Errors Caused Drone, Helicopter Collision, *National Transportation Safety Board*, Aviation Incident Final Report.

FAA, 2017: Nextgen Weather: FAQ Weather Delay, *FAA*.

FAA, 2018: Commercial Operations Branch, Part 107 UAS Operations.

FAA, 2019: Unmanned Aircraft Systems, *FAA*.

Furman, S. and Coauthors, 1999: Department of Defense Design Criteria Standard: Human Engineering. *MIL-STD-1472F*, 210 pp.

Gupta, S. and Coauthors, 2013: Review of Unmanned Aircraft System (UAS). *International Journal of Advanced Research in Computer Engineering and Technology (IJARCET)*, **Volume 2, Issue 4**.

Huerta, M, 2017: Unmanned Aircraft Systems Symposium Opening Remarks.

Kottek, M., J. Grieser, C. Beck, B. Rudolf, and F. Rubel, 2006: World Map of the Köppen-Geiger climate classification updated. *Meteorol. Z.*, **Volume 15**, 259-263 pp. DOI: 10.1127/0941-2948/2006/0130.

Kulesa, G. 2003: Weather and Aviation: How Does Weather Affect the Safety and Operations of Airports and Aviation, and How Does FAA Work to Manage Weather-related Effects? FAA's Aviation Weather Research Program.

Lott, J., 2004: The Quality Control of the Integrated Surface Hourly Database. *National Climatic Data Center*.

NCEI-ISD, 2019: Integrated Surface Database.

NCEI-IGRA, 2019: Integrated Global Radiosonde Archive.

Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM), 2019: Federal Meteorology Handbook No. 1: Surface Weather Observations and Reports.

Park, J., Lee, K., 2016: Classification of Buildings Using High Resolution UAV Image, *Advanced Science and Technology Letters*, **Volume 141** (GST 2016), 145-147 pp.

Politovich, M.K., 2015: *Encyclopedia of Atmospheric Sciences*, Second Edition. Elsevier, 160-165 pp.

Ranquist, E., and Steiner, M., 2017: Exploring the Range of Weather Impacts on UAS Operations, *18th Conference on Aviation*, Range, and Aerospace Meteorology.

Roseman, C., Argrow, B., Pinto, J., 2019: Weather Forecasts for Small Unmanned Aircraft Systems, *American Meteorological Society Conference*.

RTCA, 1984: Environmental Conditions and Test Procedures for Airborne Equipment. *RTCA DO-160B*, 227 pp.

Schaefer, J. T., and C. A. Doswell III, 1979: On the interpolation of a vector field. *Mon. Wea. Rev.*, **Volume 107**, 458–476 pp.

Wallace, R. and Coauthors, 2018: Evaluating Small UAS Near Midair Collision Risk Using AeroScope and ADS-B. *International Journal of Aviation, Aeronautics, and Aerospace*.

Werfelman, L., 2017: Pilot Weather Reports on the Decline. *Flight Safety Foundation*.

Werner, C., 2017: Fire Technology: Drones Soar Following Hurricanes.

Widseth, C, and Morss, D, 1999: Airborne Verification of Atmospheric Turbulence Using the Richardson Number, *National Weather Association*, **Volume 23, Number 4**.