IDENTIFICATION OF WEATHER INFORMATION GAPS FOR GENERAL AVIATION AND UNCREWED OPERATIONS

By

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IDENTIFICATION OF WEATHER INFORMATION

GAPS FOR GENERAL AVIATION AND

UNCREWED OPERATIONS

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Abstract: Uncrewed Aircraft Systems (UAS) represent a rapidly growing industry, with a market value of $20.8 billion in 2021 projected to grow to half a trillion dollars in 2028, and Urban Air Mobility is projected to grow from $3 billion in 2021 to $8.9 billion in 2028.. However, these fields will require advances in both air traffic management and weather systems. Existing aviation weather systems focus on weather at airports and at altitude, while UAM and UAS will both need low altitude, higher fidelity weather observation tools and prediction models. Weather Intelligent Navigation Data and Models for Aviation Planning (WINDMAP) is a NASA University Led Initiative which aims to tackle the development of next generation weather systems for UAM and UAS. Part of developing the next generation weather systems is designing the front-end applications which consumers will use to obtain and interpret weather data. To develop front-end products, as well as inform requirements for back-end products, it is important to determine customer needs, and identify customers' perceived gaps in current weather information systems. GA pilots as a group have been extensively studied for decades and their opinions and usage of weather information sources have been well documented, however UAS operators as a group have only existed for as long as their industry, and as such there is little research on them or their perceptions of weather sources. I conducted a survey to gain insight into the perceptions of both GA pilots and UAS operators to determine what weather elements they care about, what weather sources they use, what their limits are, and how they compare with each other. In the survey I found UAS operators with GA experience tend to use GA weather information sources for UAS operations, suggesting modeling future weather information systems on existing ones might work well. UAS operators tend to care most about surface winds, precipitation, and low temperatures. Additionally, I provide suggestions for future research on UAS operators based on my experience gained from conducting the survey.

TABLE OF CONTENTS

Chapter | Page

LIST OF TABLES

Table Page

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Background and Motivation

The global commercial drone market was valued at $20.8 billion in 2021 and is projected to reach a revenue of $501.4 billion in 2028 (Grand View Research, 2021). Advances in hardware and software technology are enabling more people than ever before to have access to Uncrewed Aircraft Systems (UAS) based services such as surveying (McNeil & Snow, 2016), videography (Cheng, 2015), agriculture (Grenzdörfer, Engel, & Teichert, 2008), logistics (Eun, Song, Lee, & Lim, 2019) and emergency services (Jin, Yang, Fang, & Feng, 2020). This market increase will be driven by an increase in UAS operators who will need weather information solutions tailored to their use case (Lundby, Christiansen, & Jensen, 2019).

While there is no data on losses of UAS to weather, the effect of weather on General Aviation (GA) has been well documented; weather accounted for 34 non-commercial fixed wing accidents in 2019, with 30 of those accidents being fatal (AOPA Air Safety Institute, 2021). While this is a small fraction of the total GA accidents in 2019 (1169) and a larger but still small fraction of total GA fatal accidents (212), they still represent a significant and persistent problem for GA flight (AOPA Air Safety Institute, 2021). While civilian UAS weather accidents would have minimal to no risk of loss of life, loss of property is still of concern, especially if the UAS operator relies on their drone for work.

As of now, civilian UAS use is restricted to Visual Line of Sight (VLOS). Under VLOS rules UAS operators can usually judge the weather surroundings by eye but have reported a lack of effective methods to determine wind velocities above tree-level and in urban areas or areas with generally complex terrain (Campbell, Clark, & Evans, 2017). Urban Air Mobility (UAM), is a term for air transport systems such as air taxis and UAS package delivery designed to support previously underserved by aviation, such as urban areas. UAM faces similar problems with winds, as well as problems with ice and visibility (Reiche, Cohen, & Fernando, 2021).

Existing weather information and forecasting services for aviation offered by the National Oceanic and Atmospheric Administration's (NOAA) Aviation Weather Center are targeted at the world airspace system (Aviation Weather Center). As the world airspace system changes to accommodate UAS and UAM, the aviation weather information systems will need to change along with them.

Research Overview

NASA has selected Oklahoma State University (OSU) to lead a University Led Initiative (ULI) called Weather Intelligent Navigation Data and Models for Aviation Planning (WINDMAP) to develop the next generation of aviation weather systems, with providing for UAM and UAS as the top priorities (NASA, 2020).

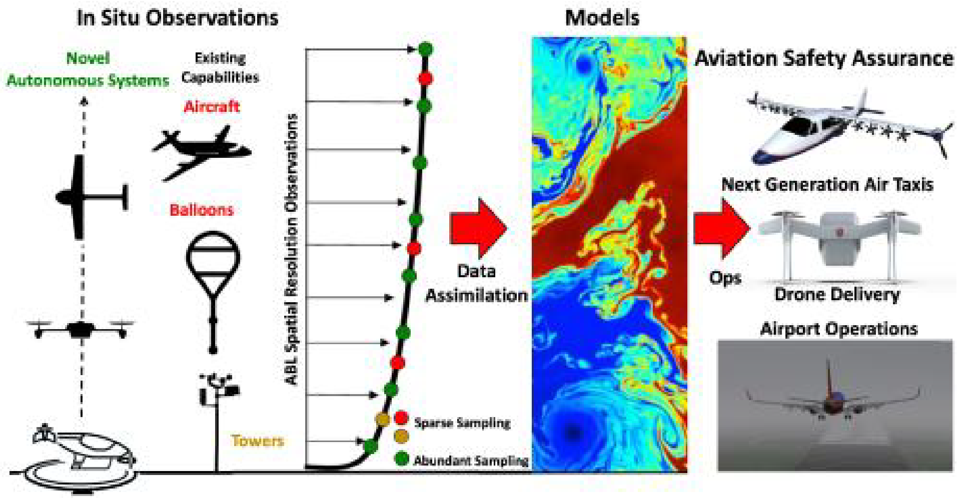

Figure 1: Concept of Operations for WINDMAP

WINDMAP spans multiple technical challenges, including development of autonomous UAS for conducting observations; determining the number and frequency of required observations; assimilating the observation data into models in real-time; and integrating the real-time forecasting into Urban Traffic Management and detect-and-avoid architectures (NASA, 2020). I did the following research in support of WINDMAP as a member of the sub-team focused on the systems engineering and integration aspect of the project. I was tasked with determining the perceived weather information gaps and weather information needs of General Aviation (GA) pilots and UAS operators. I opted to compare UAS operators and GA pilots because GA pilots and the aviation weather information systems they use have been studied for decades. To understand existing GA pilots views on weather information gaps and information needs, as well as to learn how researchers studied GA pilots, I spent a semester doing a systematic review of the literature on GA pilots' weather needs and attitudes, learning how to study GA pilots in the process (Wallace & Fala, 2021). I determined that the primary research questions would be "What weather elements matter most to UAS operators and GA pilots?", "What quantitative limits do UAS operators and GA pilots place on themselves?" and "What level of awareness and usage do UAS operators and GA pilots have of existing weather information sources?".

Survey Overview

To answer these questions, I conducted a survey of GA pilots and UAS operators. I broke this survey up into three sections, one for each major research question.

1. Weather Elements. I asked respondents questions about how frequently weather elements affected them, how satisfied they were with existing weather information system coverage of said weather elements, and weather they experienced false alarms or misses from weather information systems with respect to weather elements. These questions used a 5-point Likert-type scale.
2. Personal Limits. I asked participants to specify their personal limits in terms of maximums and minimums with respect to select weather elements in a numerical response box, whether they would be willing to fly through select conditions (yes/no/maybe), and finally if they had any additional input about their limits, they would like to share in a free response text box.
3. Weather Information Sources. I asked participants about their awareness of a list of publicly available weather information sources, both aviation specific and general use. I also asked about respondents' use of weather information sources both in planning and in flight. This section used similar 5-point Likert-type scales to the first section.

Additionally, respondents were asked demographic questions, such as how long they have been flying their respective aircraft type (UAS vs GA).

The survey was disseminated to UAS and GA interest groups and forums in mid-May 2021, with the bulk of responses coming in over the two-week period following the dissemination. Preliminary results from the survey were published at AIAA Aviation Forum 2021, noting early identification of UAS needs for improved weather products for winds aloft and convective weather (Fala & Wallace, 2021)

Thesis Overview

In this thesis, which is structured as follows, I detail the development, dissemination, analysis, and conclusions to be drawn from a survey conducted in support of WINDMAP.

Chapter 1 has introduced the challenges facing UAS and UAM as growing fields, as well as the existing challenges facing GA, and the research being done to address those challenges.

Chapter 2 expands on the background and offers further detail into the development and literature that went into the survey development.

Chapter 3 details the survey, the design choices that were made, and the modes of dissemination.

Chapter 4 analyzes and discusses the results of the survey.

Chapter 5 concludes the thesis, draws conclusions from the results of the survey, and gives recommendations for future work.

CHAPTER II

REVIEW OF LITERATURE

Background

Existing weather information and forecasting services for aviation offered by the National Oceanic and Atmospheric Administration's (NOAA) Aviation Weather Center are targeted at the world airspace system (Aviation Weather Center). GA pilots must learn to do their own weather evaluation and planning using Aviation Weather Center products before flying as part of their licensing process and as such are a population which is already familiar with doing their own weather planning (Flight Standards Service, 2018). To become an FAA-certificated remote pilot one must file an application and pass a test, then take a short online course every 24 months (Federal Aviation Administration, 2022). Part of the small UAS Airman Certification Standards requires that remote pilots have knowledge of METAR's and TAF's (Flight Standards Service, 2021). Alternatively, the FAA offers The Recreational UAS Safety Test (TRUST) certificates for recreational flyers (Federal Aviation Administration, 2022). The Advisory Circular detailing the implementation of TRUST certificates makes no mention of weather information sources for TRUST certificate holders. The FAA offers the B4UFLY Drone Airspace Safety app which focuses on providing pilots with information on airspace restrictions but offers little to no weather information (FAA, 2022).

The Drone Buddy app is an unaffiliated app with similar download numbers to the B4UFLY app on Google Play store and more reviews on the Apple App Store than B4UFLY, and it offers wind speed forecasts as a primary feature (Zhong, n.d.). The FAA also must balance public opinion on drones with the needs of drone operators, which can be difficult as the general public does not have the most favorable view of drone use outside of use for the public good (Walther, Pytlikzillig, Detweiler, & Houston, 2019).

The most comprehensive look into the weather needs of UAS operators came from an FAA commissioned report which surveyed UAS operators on their needs based on their mission classification and asked them about which weather elements (Surface Wind, Wind Aloft, Temperature, Barometric Pressure, Precipitation, Convective Weather, Clouds/Ceiling, Visibility, Turbulence and Icing) were most important to them (Campbell, Clark, & Evans, 2017). Campbell, et al. found that there were perceived information gaps in all surveyed weather elements except for precipitation and temperature, some of which could be addressed by existing or near-term FAA weather products (Campbell, Clark, & Evans, 2017). Weather information gaps are also a problem for forecasters whose job it is to forecast the weather, and UAS could be used to fill in the observational gaps in national weather service data (Houston, PytlikZillig, & Walther, 2021).

UAM's primary weather hurdles are ice, visibility, and winds (Reiche, Cohen, & Fernando, 2021). One of the main points of their paper is that seasonal weather in a number of U.S. cities would pose a problem to regular service by UAM aircraft (Reiche, Cohen, & Fernando, 2021). UAM also suffers from the complicated nature of urban wind fields, which current forecasting models have struggled to model (Steiner, 2019). Helicopter pilots are the closest we have to the eventual UAM pilots, and weather has been a contributing factor in 28% of fatal rotorcraft accidents (Ramée, Speirs, Payan, & Mavris, 2021). Personal rotorcraft flights had the highest accident and incident rates, while Helicopter Air Ambulance flights had the highest incidents and accidents due to visibility conditions of all industries (Ramée, Speirs, Payan, & Mavris, 2021).

Helicopter accidents were also found to be more frequent in areas with higher population density (Ramée, Speirs, Payan, & Mavris, 2021).

GA pilots and their training and attitudes around weather have been studied for decades. GA pilots have a demonstrated tendency to prefer simpler forms of information such as METARS (Knecht, 2008). GA pilots have been shown to view weather conditions as less severe than they are when presented on graphical weather information systems and this could be why pilots continue VFR into IMC flight, one of the leading causes of fatal weather accidents (Coyne, Latorella, & Baldwin, Influence of Graphical METARS on Pilots' Weather Judgment, 2005). Additionally, GA pilots have demonstrated a desire for in-cockpit resources with easily interpretable information (Latorella, Lane, & Garland, 2002). While missions are not particularly comparable between GA and UAS or UAM flight due to altitude, duration, and environment, pilot attitudes and behaviors could be similar, and as such studies of GA pilots might be applicable to UAS operators and future UAM pilots.

CHAPTER III

SURVEY DESIGN

Survey Design

To evaluate pilots' weather information needs and their perception of observational and weather gaps I designed and disseminated a survey to pilots and UAS operators using various social media platforms targeting aviation and UAS related groups. The survey asked pilots to rate the importance of weather elements to them, what their personal risk limits were with respect to said elements, and how familiar they are with current aviation weather products as well as more common weather products. This chapter discusses the survey design and dissemination.

Survey Overview

I chose to use a web-based survey to maximize the number and diversity of potential respondents. Internet surveys have been found to have the potential to collect data from a large and diverse sample of participants (Leong & Austin, 2006) as they provide access to individuals in locations which might otherwise be difficult to reach (Wright, 2005). However, web surveys also introduce biases. Self-selection bias results in a systemic bias where some individuals are more likely than others to complete the survey while others will ignore the survey invite. In this case self-selection bias could result in people who are more weather-aware and safety-oriented taking than the average pilot taking the survey. While there is no way to completely counteract this bias, I targeted general audience groups in the dissemination of the survey. Sampling bias is another sort of bias which can occur where the researchers are not able to reach a representative sample and under/over sample populations. I attempted to address this bias by sampling different online groups focusing on both UAS and GA pilots. There are ~275,000 licensed remote pilots and ~700,000 GA pilots in the United States, according to the latest FAA civil airmen statistics for 2021 (Federal Aviation Administration, 2022). Based on the FAA civil airmen data we would expect between a quarter and a third of the respondents to be remote pilots and two thirds to three quarters to be GA pilots. I assumed the demographic data from the survey would be similar to that of the FAA civil airmen data to be able to treat the results as a representation of the opinions of the population of licensed GA and remote pilots.

Survey Design Structure

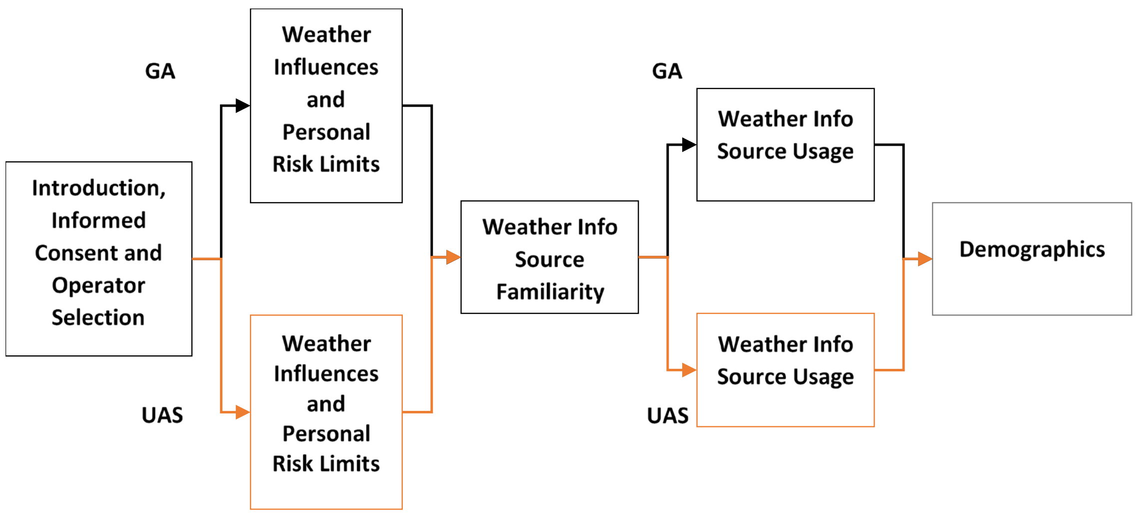

Figure 2: Survey Flow Diagram

The survey is designed to identify observational and weather gaps as well as pilot weather observation needs for both UAS and GA pilots. To find out what observational and weather gaps exist, I needed to determine what weather elements most affected pilots, and what weather information sources they frequently use, to allow me to discover whether the gaps are information based or observation based. To find out what weather elements affected pilots I asked them how frequently each weather element affected their go/no-go decision and how satisfied they were with existing weather information services for those elements. If pilots said a weather element affected them frequently but they were dissatisfied with coverage, that would mean there is a gap there. To determine what weather information sources, they used I first asked them about their individual awareness of different weather information sources, and then asked about how frequently they use those weather information sources both in planning a flight and in-flight. If a respondent is dissatisfied with a weather element but just is not aware of a weather information system which provides data about that element that would be an information gap, whereas if they were familiar, it would be an observational gap. Between those two sections I asked about the pilots' risk limits to be able to compare GA pilots and UAS operators approaches to weather risk. We ask participants about their basic demographics as well as GA and UAS specific questions. Since we want to be able to allow pilots who fly GA aircraft and UAS to be able to answer both parts of the survey, keeping the weather information source familiarity question common between them shortens the survey and makes it easier to compare different combinations of populations (participants who completed only the GA section, participants who completed only the UAS section, and participants who completed both the GA and UAS sections).

Survey Mechanics

I chose to use Qualtrics as OSU has an existing partnership with it and is easy for participants to use. To answer my research questions, I needed qualitative opinion data from pilots of both UAS and GA aircraft on how weather impacts their flight habits, and what weather information sources they use. While qualitative data could be collected from focus groups, I chose to use an online survey to reach a broader audience. Given the broad scope and large number of weather element questions and weather information source questions we wanted to ask, we needed a simple and effective method to determine pilot knowledge and opinions. Likert-type questions provided a way to get quantifiable data on pilots' subjective experiences and attitudes.

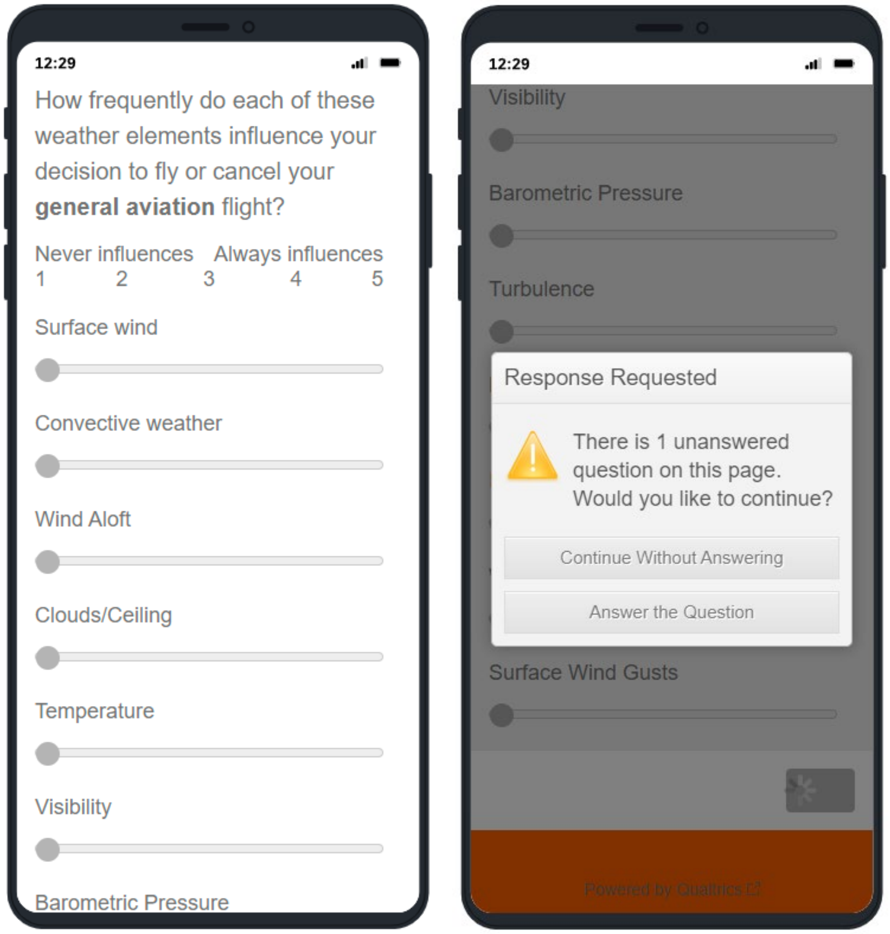

Figure 3: How a Likert-type block looked on mobile devices

For the implementation of the Likert-type questions I chose to use a five-point slider with anchoring at each end. Five-point scales are more user friendly for respondents on mobile devices (Toepoel & Funke, 2018). Sliders are a more advantageous choice than alternatives such as radio buttons as Qualtrics allows multiple statements per individual question. Using sliders allowed us to have one question per block rather than having to add a new question for each weather element/information source. Sliders were initialized to 'one' and required participant input to be recorded to reduce default bias. Default bias is where the participant leaves the default input selected and clicks 'next' on the survey (Anderson, C.J., 2003). If participants attempted to continue the survey without selecting a response, they would be presented with a pop up with the option to continue the survey and not answer the questions or to return and answer the questions as shown in Figure 2. The occupation was specified in each question in bold to make clear to those participants who are both UAS operators and GA pilots which track they are answering for in the question.

Weather Influences

To measure to what degree each weather element affects pilots' decisions to fly we used a 5-point Likert-type scale with anchoring of *never influences=1* to *always influences=5* for each of the 12 weather elements we identified: surface wind, convective weather, wind aloft, clouds/ceiling, temperature, visibility, barometric pressure, turbulence, precipitation, icing, wind shear, and surface wind gusts (Campbell, Clark, & Evans, 2017). These weather elements were selected as they represent a mostly complete range of general weather phenomena experienced in most geographic areas while not being so exhaustive as to waste participant time, and some elements had been used in prior research so we could compare with previous work (Campbell, Clark, & Evans, 2017).

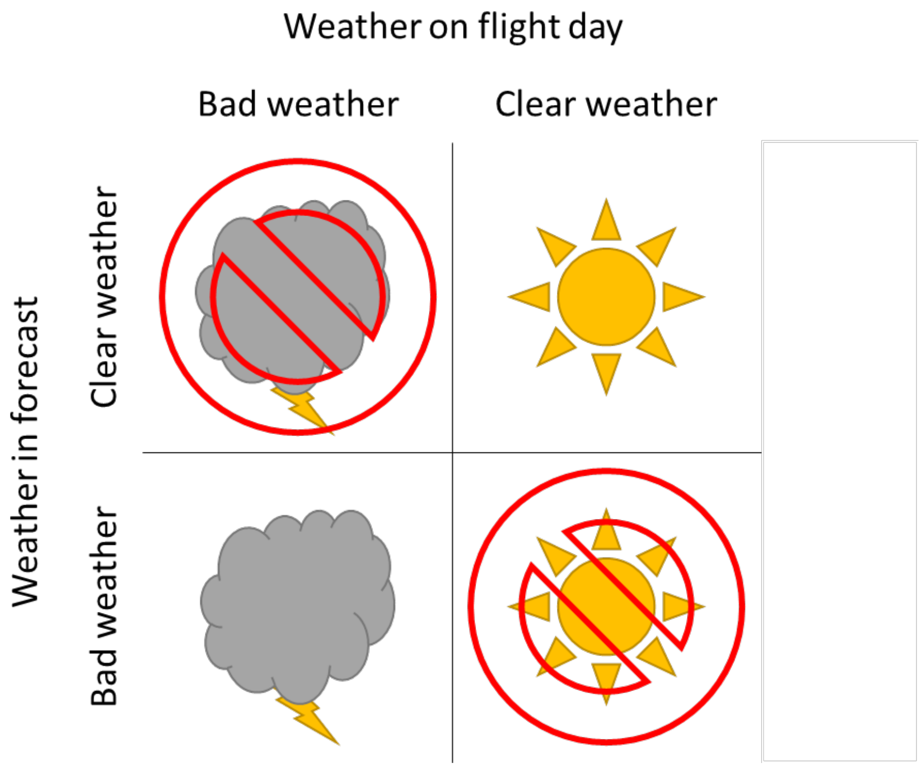

Figure 4: Signal Detection Theory of Weather Forecasting

Finally, survey respondents were presented with the question of how frequently they had experienced either a false alarm or missed signal weather report for each weather element. This question was informed by signal detection theory to find out whether current weather information sources either tended toward an overly sensitive or not sensitive enough signal detection regime. Figure 3 shows the signal detection square for weather forecasting, where the signal is the real weather, and the response is the forecast. Table 1 shows each survey question as it was presented in the survey along with the corresponding research question the survey question is intended to answer.

Table 1: Weather Element Questions

Survey Question	Research Question Answered

How frequently do each of these weather elements influence your decision to fly or cancel your **general aviation** flight? (Never to always 5-point Likert-type scale)	What weather elements affect general aviation pilots the most?
How satisfied are you with current weather products' forecasts/observations of each weather element with respect to **general aviation** flight planning? (Not at all satisfied to fully satisfied 5-point Likert-type scale)	What weather elements do pilots believe weather information products could better forecast/observe?
For each of the following weather elements, how frequently do they cause you to cancel a **general aviation** flight due to a bad forecast only to find that the forecast was wrong and you could have gone flying after all? (Never to extremely frequently 5-point Likert-type scale)	What weather elements that affect pilots do weather information products have problems with false alarms?
For each of the following weather elements, how frequently do you plan a **general aviation** flight with a good forecast only to find that the forecast was wrong, having to cancel late? (Never to extremely frequently 5-point Likert-type scale)	What weather elements that affect pilots do weather information products have problems with misses?

Personal Risk Limits

I queried participants on their personal risk minimums and maximums for various weather elements to provide additional information about pilot attitudes to the WINDMAP team on top of the data from the Likert-type questions. Nine of the questions in this section ask for specific numbers from the participants on their limits for: maximum wind speed during landing and take-off (LTO), maximum gust speed LTO, maximum crosswind speed LTO, max crosswind gust speed LTO, maximum temperature, minimum temperature, minimum visibility, minimum distance from convective weather, and minimum cloud ceiling. The numerical questions provide us with quantitative data on participants risk taking attitudes, which can give the WINDMAP team hard numbers to target. Participants were instructed in what units to put their input in, and the units requested for both the UAS, and GA pilots were in standard GA units (Celsius, knots, statute miles, etc.). While UAS operators would be more unfamiliar with this unit system, we expected more GA responses and expected GA pilots to know their limits better and in GA units. After the minimum/maximum questions, I asked participants about their willingness to fly in: forecasted icing conditions, forecasted precipitation conditions, wind shear, and flight with a front forecasted to be moving through their flight plan. These questions were asked to better understand our participants risk attitudes, as well as be able to compare the two pilot populations' willingness to fly in different forecasted conditions. The final question of this question group was an open textbox asking if there was anything else the participants would like us to know about their personal risk limits when it comes to weather.

Table 2: Survey questions and research questions answered block, personal risk limits

Survey Question or Question Group	Research question being answered

What is the maximum wind speed you would be willing to land/take off in, in knots? (And other quantitative questions)	What specific limits do the participants have? How do those limits compare with the resolution and capabilities of existing weather products?
Would you be willing to fly in X condition?	What attitudes do these participants have about the risks of flying in these conditions?
Is there anything else you would like us to know about your personal risk limits when it comes to weather?	What else can we learn about the participants risk limits?

Familiarity and Weather Product Usage

I shifted focus in this phase of the survey to attempt to find out pilots' awareness and usage of weather information products, products designed for both normal people and aviators. The first question of this block was asked only once and not split between the GA and UAS parts of the survey as all other questions except demographics were. It asked the participants familiarity with 12 different weather products: METAR, SPECI, PIREP, AIREP, SIGMET, AIRMET, G-AIRMET, TAF, Radar, Prog Charts, Satellite Imagery, ADS-B Weather Links, and weather apps/websites such as those on your phone or weather.com. This section used the same 5-point Likert-scale as used in the weather element influence section, just with anchoring at Unfamiliar to Extremely Familiar.

Following the familiarity question, I split the survey again between UAS operators and pilots, asking about how often they used the same weather products from the familiarity question in flight planning usage, and then again asking them how often they used them in-flight. These questions also utilized the 5-point Likert-scale but with an option to select that they were not familiar with the given weather product, to allow us to determine the efficacy of the product for that application by allowing the participants to say they do not know about it rather than that they do not use it even though they know about it.

Table 3: Survey questions and corresponding research questions

Survey Question	Research Question being answered
How familiar are you with the following weather products?	Is there a weather information product awareness gap between UAS and GA pilots?
Please use the sliders below to indicate your general aviation **flight planning** use of the given aviation weather product. If you have not heard of the weather product, check the "Not familiar" box.	What products do GA and UAS pilots use for flight planning? How do they differ?
Please use the sliders below to indicate your general aviation **in-flight** use of the given aviation weather product. If you have not heard of the product that is fine. If you have not heard of the weather product, check the "Not familiar" box.	What products do GA and UAS pilots use in flight? How do they differ?

Demographics

In the demographics section I asked GA pilots: what license they currently hold, what ratings and endorsements they have, how many years of aircraft flight experience they have, how many flight hours they have logged, whether their flight training was under Part 61 or Part 141, what kind of avionics they fly with, whether they use electronic flight bags, how often they fly crewed aircraft, and how often they participate in aviation safety programs and seminars. I asked UAV pilots: how many years of experience they have, what type of UAV they fly most, what the weight of the

UAV they've flown most is, how often they fly UAVs, and whether they have a remote pilot certificate. All participants were asked their age, gender identification, ethnicity and race, highest level of education completed, whether they had taken meteorology coursework, and what states they flew most often in.

Survey Dissemination

To get the approval of the Oklahoma State University Institutional Review Board (IRB), I needed to demonstrate that we took effort to protect the identities and information of survey participants. Qualtrics anonymized the data and stored it on the Qualtrics servers. The survey was approved by the IRB of OSU. The survey was disseminated via various aviation and UAS Facebook groups (Commercial sUAS Remote Pilots, Everything Drones, Student Pilot Community), subreddits (r/flying, r/drones), listservs, forums (Commercial Drone Pilots), and directly to some known drone operators at OSU's Unmanned Systems Research Institute (USRI). The post on r/Flying, a general aviation subreddit went to the front page of the subreddit the afternoon it was posted, received more interaction than the other posts and a large portion of the responses came in during the time it was on the front page. UAS groups proved harder to reach, with the r/Drones subreddit being uninterested in the survey and other drone forums and Facebook groups being inactive.

Table 4: Survey recruitment posts information

Target population	Group name/site	Number of Members	Engagement
General Aviation	reddit.com/r/flying	195,000	216 upvotes, 65 comments
Drone pilots	reddit.com/r/drones	141,000	10 upvotes, 1 comment

Drone pilots	Facebook Commercial sUAS Remote Pilots group	20,200	3 likes, 1 comment
Drone pilots	Facebook Everything Drones group	15,400	No engagement
General aviation	Facebook Student Pilot Community Group	35,400	No engagement
Drone pilots	Commercialdronepilots.com	5,200	1 like, 3 replies.

The low engagement of the posts in drone forums could be due to a few factors, primarily the recency of UASs as a hobby/professional area and having not had time to develop as much of a community as GA, as well as the division of UASs between First Person View (FPV) flight, videography, professional use, and R&D related fields/hobbies. In short, the UAS community is more fragmented due to recency of development and diversity of applications.

CHAPTER IV

SURVEY RESULTS AND ANALYSIS

Survey Results Overview

In total there were 777 responses to the survey after spam and test responses were removed. Of these 777 responses only 297 or 38% of responses were 100% complete. The response histogram, Figure 1, follows a roughly U-shaped curve, with around half of the respondents stopping just after answering the occupation question, about a hundred participants falling off between 10% and 90% completion, and just under three hundred completing the survey.

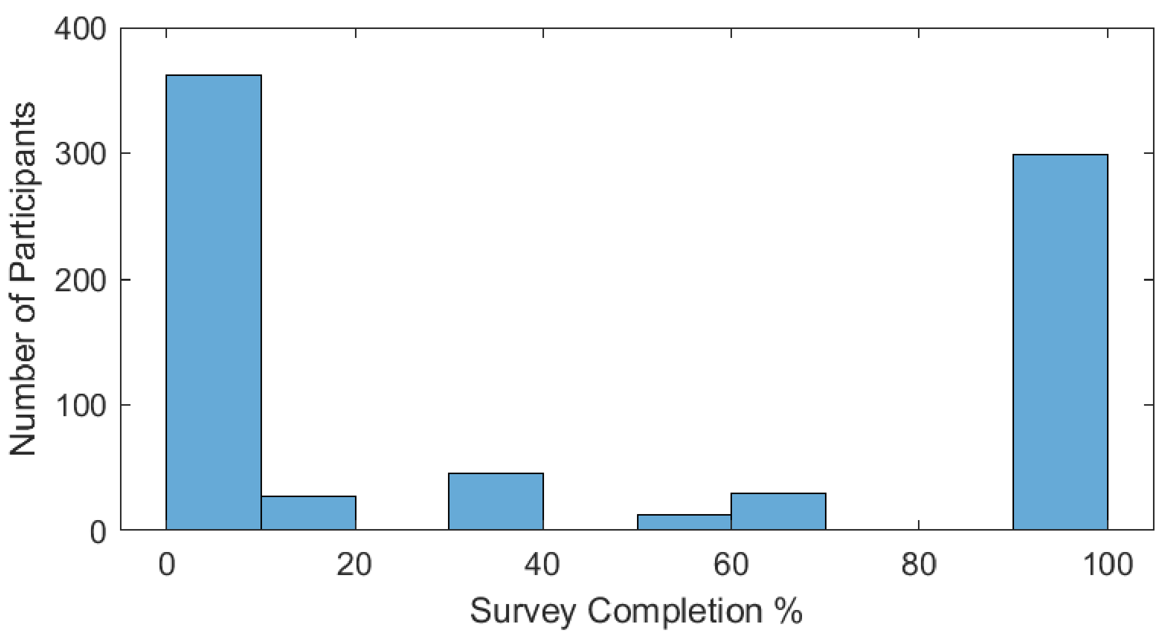

Figure 5: Survey Completion Histogram

The bulk of responses (Figure 6) came from pilots with only GA experience (634), after that came pilots with experience in both fields (93), followed by the pilots with only UAS experience (50). One of the aims of the survey was to evaluate whether UAS pilots with GA experience utilize GA weather tools in their flight planning. As such we need to be able to break up those UAS pilots with GA experience from those without. If we let U be the set of all UAS responses, and G be the set of all GA responses, we find that $U \setminus G$ is the set of all UAS responses which did not also respond to the GA side. We can also say $U \cap G$ is the intersection of U and G and therefore all respondents who answered both. By considering the subsets we can evaluate the internal consistency of a population, such as if $U \setminus G$ is different enough from $U \cap G$ in a statistically significant manner.

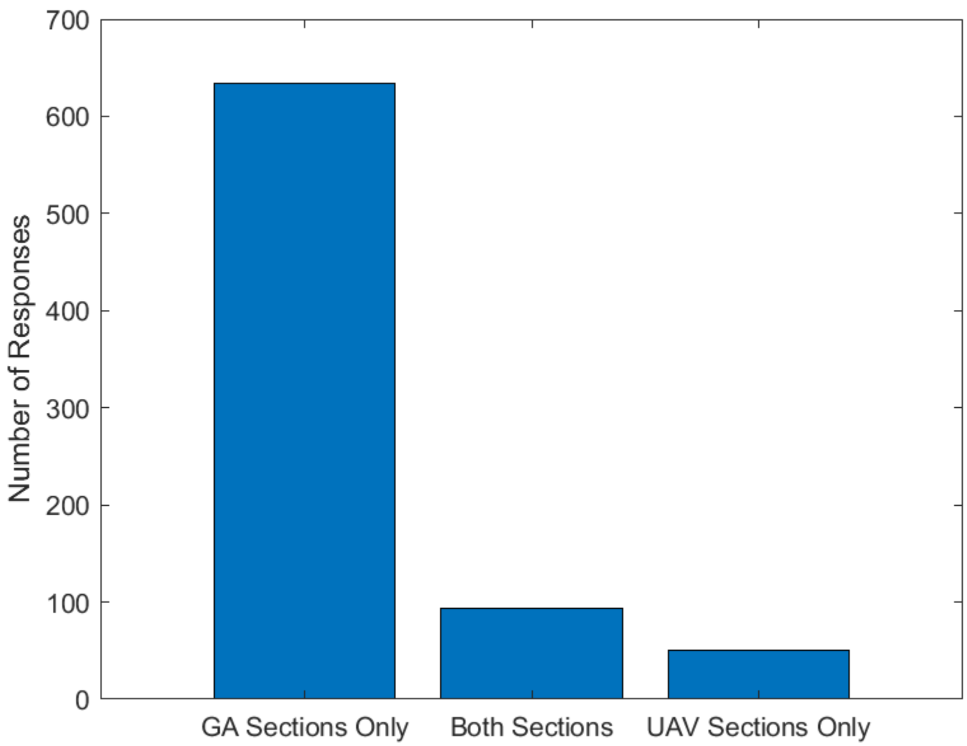

Figure 6: Number of responses from each population

Survey Analysis Considerations

The data collected in the 5-point Likert-type questions has been traditionally treated as non-continuous ordinal data requiring non-parametric analysis. However recent statistical scholarship has called this treatment into doubt, either by skepticism of the original classification put forth by (Stevens, 1946) or demonstrating the robustness of parametric methods when applied to Likert type data (Mircioiu & Atkinson, 2017). As it stands there is no definitive answer on whether to use parametric or non-parametric methods based purely on the type of data we are dealing with. I have opted to conduct both non-parametric and parametric analysis depending on the situation.

Influence Results

I want to group the U\G and U∩G subsets together to be able to have a single UAS subset to maximize the size of that subset. To justify this decision, I need to show that they are statistically similar enough, to do this I conducted a Mann-Whitney U-Test on every possible pairing of the subgroups {U\G, U∩G, G\U}, as well as G and U directly. The Mann-Whitney U-Test is a non-parametric test for equality of population medians between independent samples (Mann & Whitney, 1947). Table 5 demonstrates that U and G are internally consistent, and that the greatest distinction can be found when comparing either the intersecting set or the sets. The UAS population only differs on barometric pressure, and the GA sample only differs on visibility and wind aloft. Even these internal differences do not mean they do not have the same tendency, as visible in Figure 6. Figure 6 uses a stacked bar chart method which centers the responses around the neutral answer in order to be able to better show the tendency of the data.

Table 5: Mann-Whitney U-Test Results for U∩G vs U\G, G∩U vs G\U, and G vs U.

Weather Element	**p, U∩G vs U\G**	**p, G∩U vs G\U**	**p, G vs U**
Surface Wind	3.77E-01	8.27E-01	*5.91E-05*
Convective Weather	1.31E-01	8.75E-02	*5.26E-11*
Wind Aloft	9.71E-01	*8.45E-04*	5.13E-01
Ceiling	4.54E-01	1.78E-01	*4.40E-06*
Temperature	1.09E-01	1.05E-01	*2.27E-03*
Visibility	1.89E-01	*1.83E-02*	1.04E-01
Pressure	*1.68E-02*	8.82E-02	*8.34E-03*
Turbulence	4.03E-01	1.27E-01	*4.28E-05*
Precipitation	8.91E-01	6.16E-02	*4.49E-20*
Icing	9.80E-01	5.79E-01	*8.61E-11*

Wind Shear	3.42E-01	6.50E-01	*8.02E-08*
Surface Gusts	7.92E-01	4.17E-01	*6.62E-05*
Number of Rejections at $p < 0.05$	1	2	10

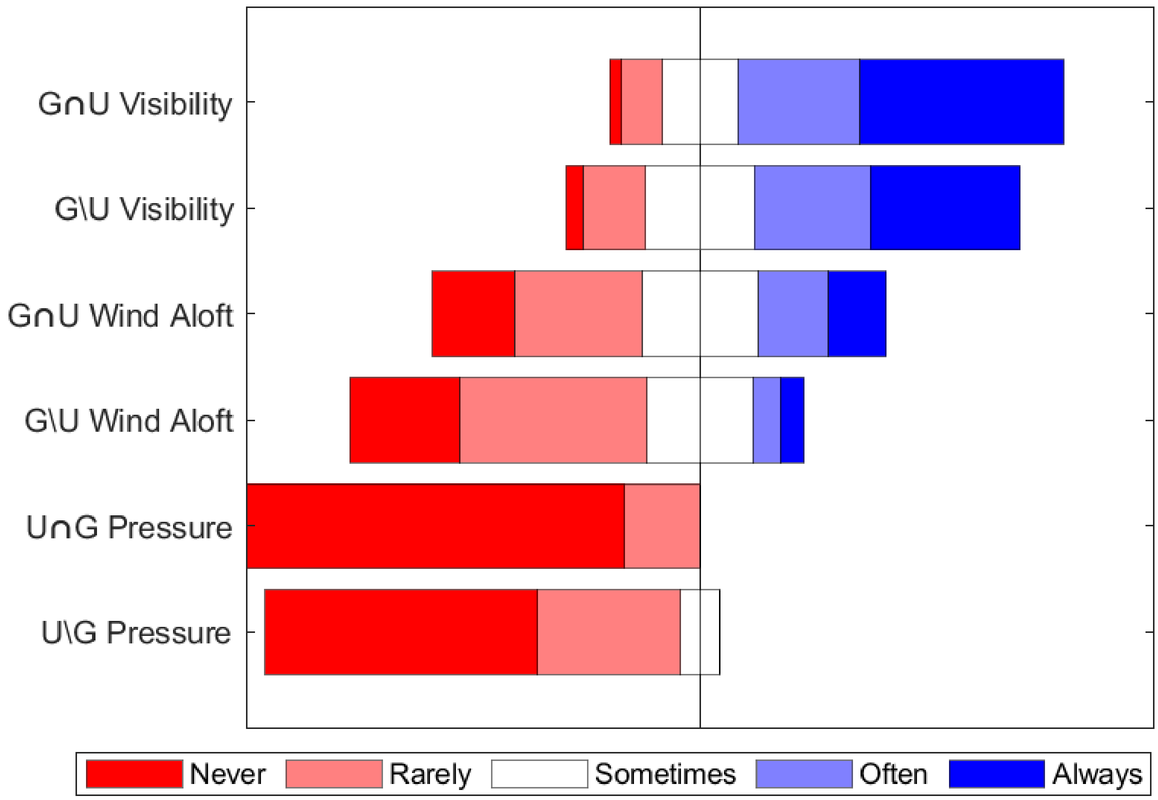

Figure 7: Likert Responses Demonstrating Internal Consistency of UAS and GA populations despite $p > 0.05$ on the weather element influences question.

I conducted a Mann-Whitney U-Test on the rest of the questions in this block and similar results were found, with internal disagreements only being statistically relevant for 1 or 2 weather elements. In the interest of brevity, the exact results can be found in the appendix. I made an error in the survey implementation in Qualtrics when creating the UAV questions for one of the signal detection theory questions when I accidentally set the question to only be viewable to respondents who answered 'pilot', so there is no U\G subset for that question, and as a result we lost ~20 responses. Given the internal consistency of the other UAV response sets this is not that big of a loss.

The descriptive statistics for the first question, seen in Table 6, demonstrate some differences in the populations. Primarily that GA pilots care significantly more about icing and convective weather, while UAS pilots care the most about surface wind, precipitation, and surface gusts. This is along the lines of what we expected when we sent out the survey, and makes sense given the restrictions and limitations on UAS.

Table 6: Descriptive statistics of question 'How frequently does the given weather element affect your go/no-go decision?'

	General Aviation Responses					UAS Responses				
Weather Element	**Mean**	**STD**	**Median**	**IQR**	**n**	**Mean**	**STD**	**Median**	**IQR**	**n**
Surface Wind	3.73	1.22	4	2	602	4.24	1.17	5	1	83
Convective Weather	4.19	1.11	5	1	603	3.00	1.61	3	4	81
Wind Aloft	2.33	1.10	2	1	596	2.58	1.54	2	3	79
Ceiling	3.99	1.09	4	2	601	3.15	1.55	3	3	80
Temperature	2.03	1.03	2	1	590	2.54	1.36	2	2	78
Visibility	3.75	1.17	4	2	601	3.44	1.42	4	3	82
Pressure	1.63	0.93	1	1	572	1.31	0.54	1	1	77
Turbulence	2.80	1.11	3	1	598	2.26	1.38	2	2	80
Precipitation	3.19	1.21	3	2	597	4.51	0.93	5	1	82
Icing	4.19	1.22	5	1	599	2.88	1.77	2	4	80
Wind Shear	3.71	1.27	4	2	593	2.71	1.59	2	3	78
Surface Gusts	3.54	1.19	4	2	599	4.05	1.26	5	2	82

I asked participants how satisfied they were with forecasts and observations for weather elements, and found that both populations seemed to be pretty satisfied with existing observation and forecasting information, with no means/medians under three. GA pilots were least satisfied with information about wind shear and turbulence, while UAS operators were least satisfied with information about wind shear and winds aloft, though these are still in the three range.

Table 7: Descriptive statistics of question 'How satisfied are you with current forecasts/observations for each weather element for flight planning?' 1 = not satisfied, 5 = satisfied

	General Aviation Responses					UAS Responses				
Weather Element	**Mean**	**STD**	**Median**	**IQR**	**n**	**Mean**	**STD**	**Median**	**IQR**	**n**
Surface Wind	4.07	0.91	4	1	483	3.75	1.13	4	2	69
Convective Weather	3.78	0.98	4	1	480	3.41	1.14	3	1	70
Wind Aloft	3.62	1.05	4	1	481	3.22	1.24	3	2	69
Ceiling	3.83	1.02	4	2	480	3.67	1.09	4	1.25	69
Temperature	4.28	0.93	5	1	481	4.16	1.00	4	1	70
Visibility	3.91	0.96	4	2	481	3.90	1.07	4	2	70
Pressure	4.14	1.00	4	2	480	3.87	1.11	4	2	68
Turbulence	3.03	1.03	3	2	480	3.29	1.15	3	1	68
Precipitation	3.74	0.96	4	1	480	3.71	0.98	4	2	70
Icing	3.47	1.07	3	1	479	3.60	1.14	4	2	67
Wind Shear	3.02	1.15	3	2	477	3.15	1.14	3	2	68
Surface Gusts	3.71	1.07	4	2	478	3.46	1.16	4	1	69

For the signal detection portion of the survey, I found that over all the existing weather service which the participants use appear to be forecasting accurately as far as not having false alarms, as evident in Table 8, and misses, in Table 9. UAS respondents reported the most false alarms, with the elements of surface wind, precipitation, and surface gusts, all with a median of three. GA respondents reported the most false alarms with cloud ceilings also with a median of three. Overall there were fewer misses, which I did not expect as I would have thought that pilots would be less likely to remember that the weather was clear when the forecast had said it was notgoing to be, but I suppose my assumption was wrong. The highest misses here are only twos, and UAS operators continue to identify surface wind, surface gust, and precipitation as the most frequent misses. GA is more spread out a bit, between surface wind, convective weather, visibility, precipitation, and surface gusts. Perhaps unsurprisingly, all of these elements (except for precipitation for GA respondents) were also the highest scoring on frequency of influence for GA flights.

Table 8: Descriptive Statistics of question 'How frequently do you have to cancel a flight due to a bad forecast only to find the weather was clear on the original date?' 1 = never, 5 = always

	General Aviation Responses					UAS Responses				
Weather Element	**Mean**	**STD**	**Median**	**IQR**	**n**	**Mean**	**STD**	**Median**	**IQR**	**n**
Surface Wind	2.18	1.08	2	2	403	2.88	1.29	3	2	60
Convective Weather	2.42	1.19	2	2	398	1.78	1.15	1	1	60
Wind Aloft	1.39	0.67	1	1	383	1.83	1.27	1	1	58
Ceiling	2.91	1.13	3	2	409	2.05	1.22	1.5	2	58
Temperature	1.26	0.58	1	0	378	1.44	0.80	1	1	57
Visibility	2.22	1.09	2	2	398	1.86	1.09	1	1.25	57
Pressure	1.14	0.49	1	0	376	1.16	0.42	1	0	56
Turbulence	1.77	0.98	1	1	384	1.67	1.06	1	1	57
Precipitation	2.17	1.15	2	2	395	2.60	1.14	3	1	60
Icing	2.05	1.24	2	2	387	1.55	1.14	1	1	56
Wind Shear	1.85	1.11	1	1	379	1.64	1.03	1	1	56
Surface Gusts	2.18	1.16	2	2	392	2.62	1.30	3	2	60

Table 9: Descriptive Statistics of question 'How frequently do you have to cancel a flight due to bad weather despite having a clear forecast beforehand?' 1 = never, 5 = always

	General Aviation Responses					UAS Responses				
Weather Element	**Mean**	**STD**	**Median**	**IQR**	**n**	**Mean**	**STD**	**Median**	**IQR**	**n**
Surface Wind	2.10	1.08	2	2	362	2.54	1.17	2	1	37
Convective Weather	1.94	1.02	2	2	362	1.53	0.71	1	1	34
Wind Aloft	1.31	0.67	1	0	360	1.72	1.11	1	1	36
Ceiling	2.52	1.08	2	1	361	1.62	0.78	1	1	34
Temperature	1.20	0.53	1	0	360	1.18	0.39	1	0	33
Visibility	1.91	0.99	2	1.25	361	1.69	1.02	1	1	35
Pressure	1.13	0.41	1	0	360	1.12	0.33	1	0	34
Turbulence	1.61	0.89	1	1	360	1.50	0.86	1	1	34
Precipitation	1.79	0.93	2	1	362	2.03	0.97	2	2	34
Icing	1.65	0.88	1	1	361	1.43	0.81	1	1	35

Wind Shear	1.62	0.92	1	1	360	1.56	0.93	1	1	34
Surface Gusts	2.07	1.12	2	2	361	2.41	1.24	2	2	37

Personal Risk Limits

The personal risk limit data required some extra processing, as there were a handful of extremeties in each category which had to be removed. Need to test whether the two populations are internally consistent, as Table 10 shows they are as internally consistent as before. Even beyond that they are directly consistent on a few limits, primarily crosswinds, maximum temps, and minimum visibility. I used a Mann-Whitney U-test again not due to the form of the data but because the population size for some of the UAS subsets get on the small side for parametric methods (n~30).

Table 10: Mann-Whitney U-Test results for personal risk limits section

Personal Limit	p, G∩U vs G\U	p, U∩G vs U\G	p, G vs U
Max. Wind LTO	6.34E-01	5.93E-01	*5.11E-14*
Max. Gust LTO	3.31E-01	*2.02E-02*	*1.05E-08*
Max. Crosswind LTO	6.46E-01	7.72E-01	1.48E-01
Max. Crosswind Gust LTO	6.11E-01	7.04E-02	4.01E-01
Max. Temperature	8.29E-02	7.89E-01	*2.80E-02*
Min. Temperature	1.86E-01	3.22E-01	*6.79E-09*
Min. Visibility	1.33E-01	5.24E-01	4.76E-01
Min. Distance to Convective Weather	5.25E-01	*3.11E-03*	*2.03E-08*
Min. Ceiling	7.45E-01	2.29E-01	*1.30E-03*
Number of Rejections at p < 0.05	0	2	6

GA pilots tended to be willing to fly in maximum winds/gust speeds about 10 kts over the maximum wind speeds the UAS pilots were willing to fly in. This changes for crosswinds, where UAS pilots stay mostly the same and GA pilots come down to the UAS level. Maximum temperatures are similar between both populations, but minimums are about 10°C less than the UAS group, which are around freezing. The reason for this might be because LiPo batteries have a performance drop off below freezing, as mentioned later on in the free response section.

Table 11 Descriptive statistics of personal limits questions

Weather limit	GA					UAS				
	Mean	STD	Median	IQR	n	Mean	STD	Median	IQR	n
Max. Wind LTO, kts	26.90	9.10	25	10	332	17.13	7.06	15	8	56
Max. Gust LTO, kts	26.27	10.13	25	15	332	17.77	9.80	16	14.5	56
Max. Crosswind LTO, kts	16.99	7.22	15	7	331	15.31	8.42	15	10	55
Max. Crosswind Gust LTO, kts	16.72	7.83	15	10	330	15.79	10.01	15	10.5	56
Max. Temperature, C	40.76	13.36	40	10	329	36.46	8.53	37	7	54
Min. Temperature, C	-12.61	16.06	-10	16	328	-1.93	11.84	0	11.5	56
Min. Visibility, miles	3.32	6.11	3	4	333	2.69	1.90	3	2	56
Min. Distance to Convective Weather, miles	18.07	13.85	20	10	330	9.25	9.36	5	7.75	55
Min. Cloud Ceiling, feet	1421	1223	1000	1500	334	888	856	600	600	57

In addition to asking for specific limits, I also asked about participants willingness to fly in/through four given weather conditions, icing, precipitation, wind shear, and weather front. The participants were able to respond with radio buttons to select 'Yes', 'No' or 'Maybe'. I chose to simply calculate the percentage each response contributes to each answer, to make it easier to compare across populations. I opted not to do any statistical comparisons between populations as I have just shown all of the data below in Table 11. From the data, GA pilots were more inclined to say 'maybe' than UAS pilots across all questions. The UAS population with no GA experience were the most likely to say no to all flight conditions, while the UAS population with GA experience were willing to fly with a weather front coming through. The largest distinction between the G and U groups was willingness to fly in precipitation which makes sense given most commercially available UAS systems can not fly in the rain.

Table 12: Answers to questions on willingness to fly through given weather conditions

	G\U	U\G	G∩U	U∩G

Willing to fly through	Maybe	No	Yes	Maybe	No	Yes	Maybe	No	Yes	Maybe	No	Yes
Icing	28%	64%	8%	6%	78%	17%	13%	78%	9%	15%	64%	21%
Precipitation	27%	4%	69%	11%	67%	22%	39%	15%	46%	8%	72%	21%
Wind Shear	39%	32%	29%	22%	72%	6%	30%	49%	21%	23%	46%	31%
Weather Front	52%	13%	35%	50%	44%	6%	38%	30%	32%	28%	31%	41%

I received and processed 179 free response comments on the personal limits section. Most of the free response comments were from GA pilots stating that limits depend on a variety of factors. As you can see in Figure 7, aircraft, VFR/IFR and icing were the the most prevalent factors on which limits depended. The main factor was aircraft and what sort of equipment it had, as well as whether the pilot was flying VFR or IFR. Pilot experience also featured prominently, with more experienced pilots, and pilots with Airline Transport Pilot certificates generally stating they had higher limits. There was a fair amount of complaints and suggestions, primarily advising the limits be split between VFR and IFR. The few UAS pilots who did answer this question were primarily pointing out that crosswinds do not exist for quadcopters. Some other UAS pilots seconded the GA pilots in saying that it depends on the airframe, for UAS primarily fixed wing vs quads. Two UAS pilots said the primary limit on temperature was due to Li-Po batteries, not their personal comfort.

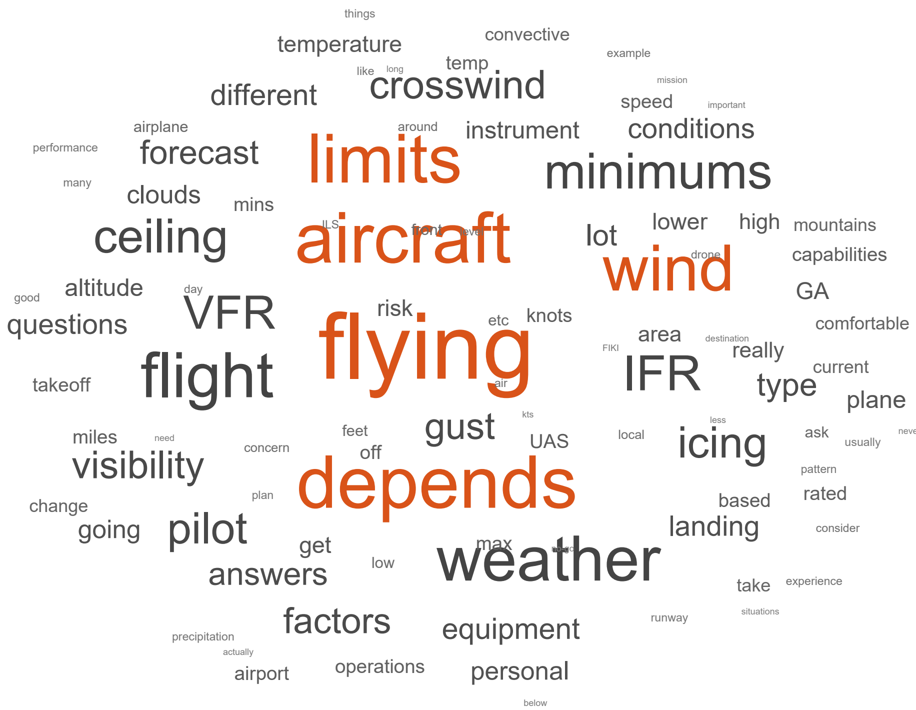

Figure 8: Word Cloud of Free Response Answers

Awareness and Usage

For the awareness and usage section, the first question is answered by each participant only once regardless of their occupation, so there are only 3 sub populations, U\G, G\U and U∩G. As we can see from the Mann-Whitney U-test results in Table 11, the GA pilot group is mostly internally consistent while the UAS group is more different statistically than just comparing the GA only group to the UAS only group. As such for our comparisons for familiarity we will be looking at the UAS only section vs the GA only section.

Table 13 Mann-Whitney U-test results for question 'What is your familiarity with the following weather elements?'

Weather Information Sources	U∩G vs U\G	G∩U vs G\U	G\U vs U\G
METAR	*1.17E-04*	8.68E-01	*9.47E-11*
SPECI	*1.51E-04*	9.84E-01	*5.22E-06*
PIREP	*6.66E-06*	3.74E-01	*3.79E-08*
AIREP	1.74E-01	8.18E-01	1.43E-01
SIGMET	*1.15E-05*	1.92E-01	*1.04E-06*

AIRMET	*6.14E-05*	3.26E-01	*8.40E-06*
GAIRMET	*2.50E-04*	5.94E-01	*1.44E-05*
TAF	*6.76E-05*	6.88E-01	*1.88E-10*
Radar	*4.65E-03*	*2.86E-02*	1.05E-01
Prog Chart	*1.66E-05*	6.03E-02	*1.62E-05*
Satellite Imagery	7.55E-02	*3.51E-03*	8.39E-01
ADS-B	*3.92E-04*	1.29E-01	*1.89E-03*
Other	3.67E-01	*2.36E-02*	3.79E-01
Number of Rejections at p < 0.05	10	3	9

All of the GA pilots were familiar with the Aviation Weather Center weather information sources, as well as the broad weather information sources, except for AIREPs. UAS operators are surprisingly familiar with METARs, but unfamiliar with the GA-specific weather information sources, as shown in Table 14.

Table 14: Descriptive Statistics of Familiarity with Weather Info Sources

Weather Info Sources	GA Familiarity					UAV Familiarity				
	Mean	STD	Median	IQR	n	Mean	STD	Median	IQR	n
METAR	4.91	0.39	5	0	270	3.71	1.45	4	3	17
SPECI	3.86	1.50	5	2	264	1.71	1.20	1	1	14
PIREP	4.41	0.95	5	1	268	2.13	1.51	1	2	15
AIREP	2.38	1.49	2	2	267	1.80	1.15	1	1.75	15
SIGMET	4.51	0.83	5	1	269	2.56	1.71	2	3.5	16
AIRMET	4.42	0.98	5	1	269	2.69	1.66	2.5	3.5	16
GAIRMET	3.46	1.60	4	3	267	1.53	0.74	1	1	15
TAF	4.86	0.58	5	0	269	3.13	1.82	3	4	16
Radar	4.56	0.79	5	1	268	4.22	1.00	5	2	18
Prog Chart	4.07	1.12	4	2	269	2.41	1.50	2	2.25	17
Satellite Imagery	4.27	1.00	5	1	267	4.35	0.86	5	1.25	17
ADS-B	3.56	1.49	4	3	266	2.38	1.20	2.5	2	16
Other	4.60	0.83	5	0	269	4.83	0.38	5	0	18

When looking at how the different respondents use weather information sources for flight planning, we find that GA pilots use METAR's, TAF's, SIGMET's, AIRMET's, Radar, and other weather sources at a high rate in planning, Table 15. On the planning and flight usage questions both GA and UAS pilots had a checkmark option to answer 'not familiar', however it appears that Qualtrics just used this to skip the question rather than record ('not familiar') seperately. This is likely the reason for the drop off in responses from the familiarity question.

Table 15: Descriptive Statistics of Planning Usage of Weather Information Sources

Weather Info Sources	GA Plan					UAV\GA Solo Plan				
	Mean	STD	Median	IQR	n	Mean	STD	Median	IQR	n
METAR	4.87	0.51	5	0	298	3.31	1.55	3	3	13
PIREP	3.77	1.23	4	2	286	2.86	1.86	3	3.75	7
AIREP	2.67	1.46	2	3	141	1.50	1.00	1	1	4
SIGMET	4.29	1.10	5	1	292	3.00	1.85	3	4	8
AIRMET	4.05	1.20	5	2	287	3.14	1.86	3	3.75	7
GAIRMET	3.85	1.34	4	2	209	1.67	1.15	1	1.5	3
TAF	4.84	0.46	5	0	293	4.11	1.36	5	1.25	9
Radar	4.22	1.04	5	1	290	4.00	1.41	5	2	16
Prog Chart	3.56	1.24	4	2	287	3.00	1.60	3	3	12
Satellite Imagery	3.58	1.22	4	2	293	3.83	1.62	5	2	18
ADS-B	3.16	1.52	3	3	255	2.27	1.42	2	2	11
Other	4.08	1.22	5	2	295	5.00	0.00	5	0	19

In terms of in-flight usage of weather products, the GA pilots continue to use METAR's, radar and ADS-B at a high level while usage of other products drops off, Table 16. It is difficult to determine much from the UAS data, given the issue with the survey given earlier, except that UAS operators continue to use common weather sources in flight as well.

Table 16: Descriptive Statistics of Flight Usage of Weather Information Sources

Weather Info Sources	GA Flight					UAV\GA Solo Flight				
	Mean	STD	Median	IQR	n	Mean	STD	Median	IQR	n
METAR	4.05	1.34	5	2	279	1.67	1.37	1	0.5	12
PIREP	3.07	1.47	3	3	270	1.33	1.00	1	0	9
AIREP	1.76	1.20	1	1	148	1.11	0.33	1	0	9
SIGMET	2.74	1.50	2	3	269	1.33	1.00	1	0	9
AIRMET	2.55	1.44	2	3	262	1.33	1.00	1	0	9
GAIRMET	2.06	1.38	1	2	204	1.13	0.35	1	0	8
TAF	3.12	1.55	3	3	271	2.00	1.49	1	2	10
Radar	3.39	1.55	4	3	271	2.86	1.70	3	4	14

Weather Info Sources	GA Flight					UAV\GA Solo Flight				
	Mean	STD	Median	IQR	n	Mean	STD	Median	IQR	n
Prog Chart	1.55	1.02	1	1	265	1.67	1.41	1	0.5	9
Satellite Imagery	2.07	1.37	1	2	270	2.86	1.61	2.5	3	14
ADS-B	3.49	1.61	4	3	246	1.91	1.38	1	2	11
Other	2.28	1.51	2	2	271	4.13	1.51	5	1	15

Demographics Overview

We collected demographic data relating to pilots experience and education, what licenses/certifications they held, and other basic demographics such as gender, race, education, age and location. Our participant population was 93% male and 5% female, 89% white and 84% had a 4 year degree or higher. Respondents were more familiar with meteorology and weather than expected, with 56% of them having taken prior coursework in aviation weather or meteorology, which could be indicateve of self-selection bias. 35% of respondents from all survey paths came from the “25-34 years old” age bracket, followed by 30% in the “18-24 year old” and 17% in the “35-44 year old” range. The response is somewhat younger than what one might expect from the general civil airmen statistics, for both GA pilots, average age of 43.7 years, and remote pilots, average age of 42.2 years (Federal Aviation Administration, 2022). The youthfulness could be due to the audience of the social media platforms skewing slightly younger than the pilot ages. Most of the participants were from California, as is visible in Figure 8, with Texas and Florida contributing the second and third most, additionally there were 28 responses from outside the US. California, Texas, and Florida are states with less extreme weather, especially less extreme winter weather, and also high populations which explains why I got more responses from those states. Perhaps most interesting is that the states with no responses, in white, all tend to be to the north of the contiguous US. Oklahoma and Indiana are likely slightly over represented due to personal connections which enabled us to get more participants to volunteer their time.

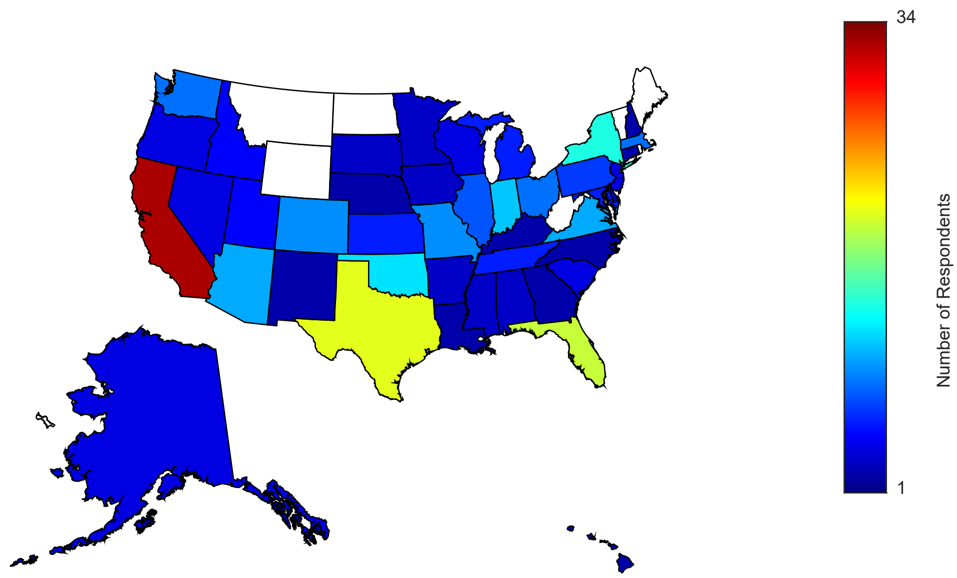

Figure 9: Map of U.S. Respondents

General Aviation Demographics

GA respondents had a median of 5 years of experience as a pilot, and a mean of 8.7 years, with some reporting upwards of 50 years of experience. Similarily, pilots surveyed reported a median of 365 total flight hours and a mean of 1200 hours, with the highest reported being 39000 flight hours. 45% of respondents were trained under Part 61, 16% under 141, 27% under some combination, and the remainder not knowing.

Half of GA respondents flew reported they flew rarely or never, while 27% flew 2-7 times per week, 13% flew once a month, 7% flew once a week and 4% flew every few months. Our GA population is thus mostly split between regular flyers and those who fly rarely. Most of the respondents held a private pilot license (43%) with airline (13%) and commerical pilots (38%) making up a larger portion than expected given the FAA statistics from 2021, with airline pilots making up only 16% and commercial pilots making up only 23% (Federal Aviation Administration, 2022).

Rougly 40% of GA pilots surveyed used glass cockpits, 30% used steam gauges and another 30% used both equally frequently. 92% of GA pilots surveyed used Electronic Flight Bags (EFBs), which are in-cockpit electronics like iPads with software which contain navigation charts, operating manuals, etc.

While most pilots reported they flew rarely or never, the next largest group flew 2-7 days per week indicating a split distribution between those who fly rarely and those who fly often.

34% of GA pilots surveyed took safety programs/courses 2 to 3 times per year, while 24% reported never attending such courses. Again, this seems to indicate a split between pilots who fly for a living and those who fly recreationally, but additional statistics would need to be done to confirm this suspicion.

UAS Demographics

The UAS participants had less experience on average in their field than the GA pilots did in theirs, with a median of 3 years, mean of 4.4 years, and max of 15 years. Rotorcraft accounted for 81% of primary UAVs reported by participants, with the remaining 19% taken up by fixed wing aircraft. 85% of the UAS operators certified were remote pilot certified, while 15% were not. Outside of three outliers in the UAV weight field of 900lb, 10000lb, and 12000lb (possibly had some military UAV pilots take this survey), most of the UAV's of participants were under 5lb with a median weight of 3lb.

CHAPTER V

CONCLUSIONS AND RECOMENDATIONS

Overview

The UAS community cares most about surface winds, surface wind gusts, and precipitation, but is overall reasonably satisfied with weather coverage of those weather elements despite most UAS operators not using aviation weather information products. UAS operators with GA experience do use some of the GA weather information sources for their UAS flights. From a survey perspective, the UAS community is more difficult to reach than the GA community and that it is better to elicit pilot responses about risk limits related to weather from direct free-response answers that allow them to detail their approach rather than direct quantities because as always, it depends.

Conclusions

UAS operators care most about wind and rain. Overall, UAS operators were fairly satisfied with existing weather information systems coverage of those weather elements. The signal design theory questions suffered a setback due to an error in the survey design, but overall showed that the existing weather information the respondents have access to is well tuned. UAS limits were somewhat more restricted than GA, but not as limited as I expected. Free response gave more insight into limits of both populations, but ultimately willingness to fly through adverse conditions depends on aircraft and pilot experience.

The awareness question was informative as it demonstrated that most UAS only operators do not have experience with GA weather information systems. The population with both UAS and GA experience applied their GA weather knowledge to their UAS flights, this was also confirmed by a free response answer. In the demographics, a surprisingly large number of participants had prior coursework in aviation weather or meteorology, across all backgrounds. This is likely due to self-selection bias and people with a prior interest in aviation weather opting to take the survey. The age of the respondents also skewed younger than the general GA and remote pilot population, suggesting the modes of dissemination may have failed to take age into account.

Recommendations

I believe that a problem facing any future work in this field will be reaching the UAS community. The lack of a cohesive UAS operator identity makes them less easily surveyed as their interest groups are more broken up across subfields than GA pilots. The extensive investment of both money and time required by GA flight encourages an identity to be built around being a GA pilot and the formation of GA pilot communities. The relatively low barrier to entry into UAS subgroups and lack of extensive universal means that they are more likely to identify with UAS operator as a whole and more likely to simply identify with their subgroup, such as FPV flying, etc.

Ideally researchers would be able to submit proposals to the FAA, and the FAA could have a default checkbox for all future license sign ups opting licensees into an email list for news on UAS and survey links. Perhaps less intrusive would be contacting UAS manufacturers and asking if they would distribute the survey through their own newsletters/promotions programs. Advertising could also be an option to get more responses from UAS operators, though it would need to be determined whether such a group can be targeted by major social media sites.

On the survey itself, I am not sure it was the best method to answer the research questions we wanted to answer. While I chose to use Likert questions and keep the question framing the same for both populations, I think that the GA units and framing likely confused at least some UAS operators.

Future UAS research along these lines will need to be done as BVLOS flight becomes more available to civilians and used for more applications, assuming the FAA continues in their general loosening of all drone restrictions. BVLOS flight will likely be far more commercialized and might have a relationship with weather more like that of existing commercial aircraft.

From my reading of the information the FAA provides about the Part 107 test there appears to be at least one section on aviation weather information sources however it is one of many sections and is only a brief part of the test. Increasing the knowledge of aviation weather information sources required by UAS operators to pass the test as well as offering online coursework for UAS operators could be a good option for increasing weather information source literacy among UAS operators.

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APPENDICES

Weather Survey

Start of Block: Consent Form

Q1 Dear pilots and UAV operators, My name is JW Wallace and I am a master's student working with Dr. Nicoletta Fala at the Department of Mechanical and Aerospace Engineering at Oklahoma State University. Our research aims to improve weather product accuracy and availability. We are seeking your input on how you use weather products in your flying and your satisfaction with existing weather products. . The motivation behind this research is the rapidly growing areas of Unmanned Aerial Systems (UAS) operations and Urban Air Mobility (UAM). Both UAS and UAM operations in the future will rely heavily on weather forecasting and observation technologies which we are currently researching. The input you provide on how you use existing weather products will help us identify gaps in weather information and areas for improvement. This survey will ask you questions about your awareness and usage of weather products, which weather elements affect you most in your operations, and how well weather products meet your information needs with respect to specific weather elements. This survey should take you around 20 minutes. During the survey, you will not be able to go back to the previous questions. You may stop the survey at any time without any repercussion to you. No personally identifiable information will be collected. All responses will be anonymous and reviewed in aggregate at the end of the study. Your participation in this survey is voluntary. You must be at least 18 years old to participate in this research. The research team works to ensure confidentiality to the degree permitted by technology. It is possible, although unlikely, that unauthorized individuals could gain access to your responses because you are responding online. However, your participation in this online survey involves risks similar to a person's everyday use of the internet. If you have concerns, you should consult the survey provider privacy policy at https://www.qualtrics.com/support/survey-platform/getting-started/data-protection-privacy/. Thank you for your time and your cooperation. Your responses are greatly appreciated and will hopefully enable the development of new and improved weather products for UAS, UAM, and General Aviation. If you have any questions regarding the survey, please feel free to contact the researchers directly either at jw.wallace@okstate.edu or nfala@okstate.edu. You can also reach the Institutional Review Board (IRB) staff at https://research.okstate.edu/compliance/irb/irb-contacts.html

End of Block: Consent Form

Start of Block: Key demographics

Q49 Are you a pilot and/or a UAV operator? (select all that apply)

▢ Pilot (1)

▢ UAV operator (2)

End of Block: Key demographics

'Start of Block: GA Hazards

Q58 This block of questions will ask you how different weather elements affect you **as a GA pilot** and how satisfied you are with current weather products' ability to provide you information about weather elements.

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = Pilot

Q45 How frequently do each of these weather elements influence your decision to fly or cancel your **general aviation** flight?

	Never influences				Always influences
	1	2	3	4	5

Surface wind ()

Convective weather ()

Wind Aloft ()

Clouds/Ceiling ()

Temperature ()

Visibility ()

Barometric Pressure ()

Turbulence ()

Precipitation ()

Icing ()

Wind Shear ()

Surface Wind Gusts ()

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = Pilot

Q16 How satisfied are you with current weather products' forecasts/observations of each weather element with respect to **general aviation** flight planning?

Not at all satisfied Extremely satisfied

	1	2	3	4	5
Surface wind ()					
Convective weather ()					
Wind Aloft ()					
Clouds/Ceiling ()					
Temperature ()					
Visibility ()					
Barometric Pressure ()					
Turbulence ()					
Precipitation ()					
Icing ()					
Wind Shear ()					
Surface Wind Gusts ()					

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = Pilot

Q49 For each of the following weather elements, how frequently do they cause you to cancel a **general aviation** flight due to a bad forecast only to find that the forecast was wrong and you could have gone flying after all?

	Never			Extremely Frequently
1	2	3	4	5

Surface wind ()	
Convective weather ()	
Wind Aloft ()	
Clouds/Ceiling ()	
Temperature ()	
Visibility ()	
Barometric Pressure ()	
Turbulence ()	
Precipitation ()	
Icing ()	
Wind Shear ()	
Surface Wind Gusts ()	

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = Pilot

Q50 For each of the following weather elements, how frequently do you plan a **general aviation** flight with a good forecast only to find that the forecast was wrong, having to cancel late?

	Never				Extremely Frequently
	1	2	3	4	5
Surface wind ()					
Convective weather ()					
Wind Aloft ()					
Clouds/Ceiling ()					
Temperature ()					
Visibility ()					
Barometric Pressure ()					
Turbulence ()					
Precipitation ()					
Icing ()					
Wind Shear ()					
Surface Wind Gusts ()					

End of Block: GA Hazards

Start of Block: Personal Limits GA

Q43 What are your personal limits for the following weather factors with respect to a **general aviation** flight?

Q44 What is the maximum windspeed you would be willing to land/take off in, in knots?

____

Q62 What is the maximum gust speed you would be willing to land/take off in, in knots?

____

Q60 What is the maximum **crosswind** speed you would land/take off in, in knots?

____

Q63 What is the maximum **crosswind** gust speed you would land/take off in, in knots?

____

Q45 What is the maximum temperature you would fly in, in Celsius?

____

Q46 What is the minimum temperature you would fly in, in Celsius?

____

Q50 What is the minimum visibility you would fly in, in statute miles?

____

Q65 What is the minimum distance from convective weather you would fly in, in nautical miles?

____

Q51 What is the minimum cloud ceiling you would fly in, in feet?

____

Q48 Would you be willing to fly in forecasted icing conditions?

- ○ Yes (1)
- ○ No (2)
- ○ Maybe (3)

Q49 Would you be willing to fly in forecasted precipitation conditions?

- ○ Yes (1)
- ○ No (2)
- ○ Maybe (3)

Q64 Would you be willing to fly through wind shear?

- ◯ Yes (1)
- ◯ No (2)
- ◯ Maybe (3)

Q66 Would you be willing to fly with a front forecasted to be moving through your flight plan?

- ◯ Yes (1)
- ◯ No (2)
- ◯ Maybe (3)

Q49 Is there anything else you would like us to know about the your personal risk limits when it comes to weather?

____

____

____

____

____

End of Block: Personal Limits GA

Start of Block: UAS Weather hazards

Q59 This block will ask you how different weather elements affect you **as a UAS operator** and how satisfied you are with current weather products' ability to provide you information about weather elements.

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = UAV operator

Q14 How frequently do each of these weather elements influence your decision to fly or cancel your **unmanned aerial systems** operations?

	Never influences				Always influences
	1	2	3	4	5

Surface wind ()	
Convective weather ()	
Wind Aloft ()	
Clouds/Ceiling ()	
Temperature ()	
Visibility ()	
Barometric Pressure ()	
Turbulence ()	
Precipitation ()	
Icing ()	
Wind Shear ()	
Surface Wind Gusts ()	

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = UAV operator

Q16 How satisfied are you with current weather products' forecasts/observations of weather elements with respect to **unmanned aerial systems** operations?

Not at all satisfied Extremely satisfied

	1	2	3	4	5
Surface wind ()					
Convective weather ()					
Wind Aloft ()					
Clouds/Ceiling ()					
Temperature ()					
Visibility ()					
Barometric Pressure ()					
Turbulence ()					
Precipitation ()					
Icing ()					
Wind Shear ()					
Surface Wind Gusts ()					

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = UAV operator

Q51

For each of the following weather elements, how frequently do they cause you to cancel a

UAS operation due to a bad forecast only to find that the forecast was wrong and you could have completed the flight after all?

	Never				Extremely Frequently
	1	2	3	4	5
Surface wind ()					
Convective weather ()					
Wind Aloft ()					
Clouds/Ceiling ()					
Temperature ()					
Visibility ()					
Barometric Pressure ()					
Turbulence ()					
Precipitation ()					
Icing ()					
Wind Shear ()					
Surface Wind Gusts ()					

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = Pilot

Q52 For each of the following weather elements, how frequently do you plan a UAS operation with a good forecast only to find that the forecast was wrong, having to cancel late?

	Never		Extremely Frequently	
1	2	3	4	5

Surface wind ()	
Convective weather ()	
Wind Aloft ()	
Clouds/Ceiling ()	
Temperature ()	
Visibility ()	
Barometric Pressure ()	
Turbulence ()	
Precipitation ()	
Icing ()	
Wind Shear ()	
Surface Wind Gusts ()	

End of Block: UAS Weather hazards

Start of Block: Personal Limits UAS

Q140 What are your personal limits for the following weather factors with respect to **UAS** operations? For the following questions, assume you are operating with the platform you most frequently use.

Q141 What is the maximum windspeed you would be willing to land/take off in, in knots?

____

Q142 What is the maximum gust speed you would be willing to land/take off in, in knots?

____

Q143 What is the maximum crosswind speed you would land/take off in, in knots?

____

Q144 What is the maximum crosswind gust speed you would land/take off in, in knots?

____

Q145 What is the maximum temperature you would fly in, in Celsius?

____

Q146 What is the minimum temperature you would fly in, in Celsius?

____

Q147 What is the minimum visibility you would fly in, in statute miles?

____

Q148 What is the minimum distance from convective weather you would fly in, in nautical miles?

____

Q149 What is the minimum cloud ceiling you would fly in, in feet?

____

Q150 Would you be willing to fly in forecasted icing conditions?

○ Yes (1)

○ No (2)

○ Maybe (3)

Q151 Would you be willing to fly in forecasted precipitation conditions?

○ Yes (1)

○ No (2)

○ Maybe (3)

Q152 Would you be willing to fly through wind shear?

- ◯ Yes (1)
- ◯ No (2)
- ◯ Maybe (3)

Q153 Would you be willing to fly with a front forecasted to be moving through your flight plan?

- ◯ Yes (1)
- ◯ No (2)
- ◯ Maybe (3)

Q154 Is there anything else you would like us to know about the your personal risk limits when it comes to weather?

____

____

____

____

____

End of Block: Personal Limits UAS

Start of Block: Familiarity

Q19 How familiar are you with the following weather products?

	Unfamiliar				Extremely Familiar
	1	2	3	4	5

METAR ()	
SPECI ()	
PIREP ()	
AIREP ()	
SIGMET ()	
AIRMET ()	
G-AIRMET ()	
TAF ()	
Radar ()	
Prog Charts ()	
Satellite Imagery ()	
ADS-B Weather Links ()	
Weather app on your phone, weather.com, local news weather, etc. ()	

End of Block: Familiarity

Start of Block: GA Weather products

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = Pilot

Q28 This next series of questions will ask about your experience with weather decision making and weather products **as a general aviation pilot**.

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = Pilot

Q21 Please use the sliders below to indicate your general aviation flight **planning** use of the given aviation weather product. If you have not heard of the weather product, check the "Not familiar" box.

Never use	Always use	Not familiar

1	2	3	4	5

METAR ()	
PIREP ()	
AIREP ()	
SIGMET ()	
AIRMET ()	
G-AIRMET ()	
TAF ()	
Radar/NexRad ()	
Prog Charts ()	
Satellite Imagery ()	
ADS-B Weather Links ()	
Weather app on your phone, weather.com, local news weather, etc. ()	

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = Pilot

Q22 Please use the sliders below to indicate your general aviation in-flight use of the given aviation weather product. If you have not heard of the product that is fine. If you have not heard of the weather product, check the "Not familiar" box.

Never use		Always use		Not familiar
1	2	3	4	5

METAR ()	
PIREP ()	
PIREP ()	
AIREP ()	
SIGMET ()	
AIRMET ()	
G-AIRMET ()	
TAF ()	
Radar/NexRad ()	
Prog Charts ()	
Satellite Imagery ()	
ADS-B Weather Links ()	
Weather app on your phone, weather.com, local news weather, etc. ()	

End of Block: GA Weather products

Start of Block: UAS Weather products

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = UAV operator

Q16 This series of questions will ask you about your experience with weather and weather products **as a UAS operator**.

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = UAV operator

Q24 Please use the sliders below to indicate your unmanned aerial systems operations **planning** use of the given aviation weather product. If you have not heard of the weather product, check the "Not familiar" box.

Never use		Always use		Not familiar
1	2	3	4	5

METAR ()	
PIREP ()	
AIREP ()	
SIGMET ()	
AIRMET ()	
G-AIRMET ()	
TAF ()	
Radar/NexRad ()	
Prog Charts ()	
Satellite Imagery ()	
ADS-B Weather Links ()	
Weather app on your phone, weather.com, local news weather, etc. ()	

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = UAV operator

Q25 Please use the sliders below to indicate your unmanned aerial systems operation **in-flight** use of the given aviation weather product. If you have not heard of the weather product, check the "Not familiar" box.

Never use		Always use		Not familiar
1	2	3	4	5

METAR ()	
PIREP ()	
AIREP ()	
SIGMET ()	
AIRMET ()	
G-AIRMET ()	
TAF ()	
Radar/NexRad ()	
Prog Charts ()	
Satellite Imagery ()	
ADS-B Weather Links ()	
Weather app on your phone, weather.com, local news weather, etc. ()	

End of Block: UAS Weather products

Start of Block: Demographics

Q27 You are almost done! We will next ask you some quick demographic questions that will allow us to group our results. You may skip any question you are not comfortable answering.

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = Pilot

Q37 What pilot's license do you currently hold?

- ◯ No certificate (1)
- ◯ Student (2)
- ◯ Sport (3)
- ◯ Recreational (4)
- ◯ Private (5)
- ◯ Commercial (6)
- ◯ Airline Transport (7)

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = Pilot

Q39 Which ratings or endorsements do you currently have?

▢Single-engine (1)

▢Multi-engine (2)

▢Instrument (3)

▢Rotorcraft-Helicopter (4)

▢Glider (5)

▢Lighter-than-air (6)

▢Seaplane (7)

▢Tailwheel (8)

▢High altitude (9)

▢High performance (10)

▢Flight instructor (11)

▢Instrument flight instructor (12)

▢Multi-engine flight instructor (13)

☐ Rotorcraft-gyroplane (14)

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = Pilot

Q41 How many years of aircraft flying experience do you have? Round to the nearest year.

____

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = Pilot

Q47 How many flight hours do you have logged (approximately)?

____

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = Pilot

Q43 Was your flight training under Part 61 or Part 141?

○ Part 61 (1)

○ Part 141 (2)

○ Combination/both (3)

○ I do not know (4)

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = Pilot

Q45 What kind of avionics do you most frequently use in your flying?

○ Mostly steam gauges (1)

○ Mostly glass cockpit (2)

○ I use both equally frequently (3)

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = Pilot

Q56 Do you use electronic flight bags in-flight? For example iPads, etc.

○ Yes (1)

○ No (2)

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = Pilot

Q49 How often do you fly crewed aircraft?

○ 2-7 days a week (1)

○ Once a week (2)

○ Once a month (3)

○ Once every few months (4)

○ Rarely/never (5)

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = Pilot

Q51 How often do you participate in aviation safety programs and seminars (such as WINGS, FAASTeam seminars, AOPA training videos, etc.)?

○ Monthly (1)

○ 2-3 times a year (2)

○ Once a year (3)

○ Once every two years (4)

○ Never (5)

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = UAV operator

Q43 How many years of UAV flying experience do you have? Round to the nearest year.

____

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = UAV operator

Q40 What type of UAV do you fly most?

- ◯ Fixed Wing (1)
- ◯ Rotorcraft (2)

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = UAV operator

Q42 What is the weight of your most flown UAV in pounds? Round to the nearest pound (1 pound = 0.454 kg)

____

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = UAV operator

Q42 How often do you fly UAVs?

○ 2-7 days a week (1)

○ Once a week (2)

○ Once a month (3)

○ Once every few months (4)

○ Rarely/never (5)

Display This Question:

If Are you a pilot and/or a UAV operator? (select all that apply) = UAV operator

Q48 Do you have your Remote Pilot Certificate for sUAS operations?

○ Yes (1)

○ No (2)

Page Break

Q29 How old are you?

- ◯ 18-24 years old (1)
- ◯ 25-34 years old (2)
- ◯ 35-44 years old (3)
- ◯ 45-54 years old (4)
- ◯ 55-64 years old (5)
- ◯ 65 years or older (6)

Q31 What is your gender?

- ◯ Male (1)
- ◯ Female (2)
- ◯ Other (3) ____
- ◯ Do not wish to specify (4)

Q29 Are you Spanish, Hispanic, or Latino?

- ◯ Yes (1)
- ◯ None of these (2)
- ◯ Prefer not to say (3)

Q22 Choose one or more races that you consider yourself to be:

- ▢ White (1)
- ▢ Black or African American (2)
- ▢ American Indian or Alaska Native (3)
- ▢ Asian (4)
- ▢ Native Hawaiian or Pacific Islander (5)
- ▢ Other (6) ____

Q33 What is the highest level of education you have completed?

- ○ Some high school (1)
- ○ High school graduate or equivalent (2)
- ○ Some college (3)
- ○ 2-year degree (11)
- ○ 4-year degree (12)
- ○ Master's degree (13)
- ○ Doctorate or Professional degree (14)

Q27 Have you taken coursework in meteorology or aviation weather?

○ Yes (1)

○ No (2)

○ Prefer not to answer (3)

Q55 In which state do you fly in most often?

▼ Alabama (1) ... I do not reside in the United States (53)

End of Block: Demographics

Oklahoma State University Institutional Review Board

Date:	02/09/2022
Application Number:	IRB-22-49
Proposal Title:	UAS and GA Weather Needs Focus Groups
Principal Investigator:	
Nicoletta Fala Co-Investigator(s):	
Faculty Adviser:	
Project Coordinator:	
Research Assistant(s):	Jw Wallace, Scout Hernandez
Processed as:	Exempt
Exempt Category:	

Status Recommended by Reviewer(s): Approved

The IRB application referenced above has been approved. It is the judgment of the reviewers that the rights and welfare of individuals who may be asked to participate in this study will be respected, and that the research will be conducted in a manner consistent with the IRB requirements as outlined in 45CFR46.

This study meets criteria in the Revised Common Rule, as well as, one or more of the circumstances for which continuing review is not required. As Principal Investigator of this research, you will be required to submit a status report to the IRB triennially.

The final versions of any recruitment, consent and assent documents bearing the IRB approval stamp are available for download from IRBManager. These are the versions that must be used during the study.

As Principal Investigator, it is your responsibility to do the following:

1. Conduct this study exactly as it has been approved. Any modifications to the research protocol must be approved by the IRB. Protocol modifications requiring approval may include changes to the title, PI, adviser, other research personnel, funding status or sponsor, subject population composition or size, recruitment, inclusion/exclusion criteria, research site, research procedures and consent/assent process or forms.
2. Submit a request for continuation if the study extends beyond the approval period. This continuation must receive IRB review and approval before the research can continue.
3. Report any unanticipated and/or adverse events to the IRB Office promptly.
4. Notify the IRB office when your research project is complete or when you are no longer affiliated with Oklahoma State University.

Please note that approved protocols are subject to monitoring by the IRB and that the IRB office has the authority to inspect research records associated with this protocol at any time. If you have questions about the IRB procedures or need any assistance from the Board, please contact the IRB Office at 405-744- 3377 or irb@okstate.edu.

Sincerely,

Oklahoma State University IRB

VITA

J.W. Wallace

Candidate for the Degree of

Master of Science

Thesis: IDENTIFICATION OF WEATHER INFORMATION GAPS FOR GENERAL AVIATION AND UNCREWED OPERATIONS

Major Field: Mechanical and Aerospace Engineering

Biographical:

Education:

Completed the requirements for the Master of Science in Mechanical and Aerospace Engineering at Oklahoma State University, Stillwater, Oklahoma in July, 2022.

Completed the requirements for the Bachelor of Science in Aerospace Engineering at Oklahoma State University, Stillwater, Oklahoma in 2020.

Completed the requirements for the Bachelor of Science in Mechanical Engineering at Oklahoma State University, Stillwater, Oklahoma in 2020.

Experience:

Graduate Teaching Assistant
Graduate Research Assistant
Undergraduate Teaching Assistant
Undergraduate Research Assistant

Professional Memberships:

Tau Beta Pi

American Institute for Aeronautics and Astronautics