A TARGETED APPROACH TO PROVIDE WEATHER GUIDANCE FOR GENERAL AVIATION PILOTS BASED ON ESTIMATED TIME OF DEPARTURE AND PERSONAL WEATHER MINIMUMS

by

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ABSTRACT

SCOTT C. DENNSTAEDT. A Targeted Approach to Provide Weather Guidance for General Aviation Pilots Based on Estimated Time of Departure and Personal Weather Minimums. (Under the direction of DR. MATTHEW D. EASTIN)

Over the last two decades, general aviation pilots in the United States, especially those who fly light fixed-wing aircraft and helicopters, have portrayed high rates of vulnerability to weather-related accidents. This high vulnerability rate is in stark contrast to the increased availability of weather reports and forecasts, which has vastly improved given the wide variety of weather guidance now available online and in the cockpit. More specifically, VFR (Visual Flight Rules) into IMC (instrument meteorological conditions) flights is the leading cause of fatal weather-related accidents. A common contributor to these fatal accidents is the pilot's inability to definitively assess the hazard prior to departure from the relevant weather guidance available. Therefore, it is hypothesized in this research that the lack of sufficient weather reports and forecasts are not a core dilemma, but instead the primary contributing factor is an inaccurate or incomplete weather assessment by pilots before a flight.

In this light, it has become apparent that pilots need a well-integrated route-based application that simplifies and organizes weather guidance in a way that requires less technical interpretation, quantifies the risk and gives time-based options to minimize a pilot's exposure to adverse weather. Consequently, this presents the opportunity for a targeted software application that will eliminate or significantly reduce weather-related accidents especially for pilots planning VFR flights.

This research therefore developed a clear assessment of weather-related accidents through a review of the literature and a questionnaire-based survey given to a group of general

aviation pilots who fly light fixed-wing aircraft and helicopters in the United States. From these responses, a standard set of personal weather minimum categories was developed based on key adverse weather conditions to evaluate weather-related risks. This included the creation of twelve personal minimum categories that encapsulate the ceiling height, surface visibility and surface wind as well as the risk of airframe icing, turbulence and convective potential that are evaluated for the departure and destination airports and along the route of flight as applicable.

The product of this research created an automated online decision-making tool that downloads and stores the latest weather forecasts for key aviation weather variables that contribute to accidents. The application accepts and stores the pilot's personal weather minimums and evaluates these against the weather along the pilot's proposed route of flight. The results are depicted graphically in an intuitive way to quantify the overall personal exposure to adverse weather. This is encapsulated in a departure advisor that depicts the personal risk relative to the time of departure over the next 2-3-day period. Moreover, an interactive map and vertical profile was created to allow the pilot to visualize in time and space these weather threats of IMC, wind, airframe icing and turbulence along the pilot's route. With this time-based approach and intuitive visualizations, such a tool if used prior to a flight will allow GA pilots to choose the optimal time to depart and limit most accidents due to encounters with adverse weather, especially those related to VFR into IMC.

ACKNOWLEDGEMENTS

Throughout the writing of this dissertation I have received a tremendous amount of support and assistance from many people over the course of my research.

I would first like to thank my supervisor, Professor Matthew Eastin, whose guidance throughout this process was invaluable in crafting the right words and keeping my topic on target. Your insightful feedback encouraged me to sharpen my thinking and brought my research and writing to a higher level.

I would like to acknowledge my colleagues Bob Glahn, Jeffrey Craven, Phillip Shafer, and Judy Ghiradelli from the National Weather Service, Meteorological Development Laboratory for their historical and technical insights into the National Blend of Models and Model Output Statistics forecasts.

I am in special debt to my colleagues Bob Sharman, Ben Bernstein and Chuck Doswell. Their respective expertise in turbulence, airframe icing and convection has been a key contributor of my passion for this research. Throughout the last two decades, they have been willing to answer my countless questions without hesitation and their continued research and dedication to further our collective understanding of weather threats to the general aviation community has been truly an inspiration.

Lastly, I would like to thank my close friends and fellow aviators, David Lederman and Chris O’Brien, who have provided countless, and sorely needed guidance with stimulating discussions on how to process “big data” and manage server infrastructure for this research and application.

DEDICATION

This research is dedicated to my wife and business partner, Kate, who has been a constant source of encouragement and support especially with all of the added stress of maintaining a business while attending graduate school during a pandemic. I am truly thankful for having you in my life and being a beacon of hope when I needed it the most. This work is also dedicated to all of my students of weather who have taught me that education, not experience, is the key to a long and enjoyable flying career.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	Advisory Circular
ADDS	Aviation Digital Data Service
AGL	Above Ground Level
AIM	Aeronautical Information Manual
AIRMET	Airman’s Meteorological Information
AME	Aviation Medical Examiner
AOPA	Aircraft Owners and Pilots Association
API	Application Programming Interface
ASOS	Automated Surface Observing System
ATC	Air Traffic Control
ATP	Airline Transport Pilot
AWC	Aviation Weather Center
AWOS	Automated Weather Observing System
AWS	Amazon Web Services
CAT	Clear Air Turbulence
CFR	Code of Federal Regulations
CBT	Computer-Based Training
CFIT	Controlled Flight Into Terrain
CIP	Current Icing Product
COPA	Cirrus Owners and Pilots Association
CVD	Color Vision Deficiency
CWA	Center Weather Advisory

DAS	Digital Aviation Services
DMA	Designated Mountainous Area
EAA	Experimental Aircraft Association
EDR	Eddy Dissipation Rate
EFB	Electronic Flight Bag
ETA	Estimated Time of Arrival
FAA	Federal Aviation Administration
FIP	Forecast Icing Product
GA	General Aviation
GFA	Graphical Forecasts for Aviation
GFE	Graphical Forecast Editor
GFS	Global Forecast System
G-AIRMET	Graphical Airman's Meteorological Advisory
GRIB	Gridded Binary
GLMP	Gridded LAMP
GTG	Graphical Turbulence Guidance
HFACS	Human Factors Accident Classification System
HRRR	High Resolution Rapid Refresh
ICAO	International Civil Aviation Organization
IDW	Inverse Distance Weighting
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
IPS	Ice Protection System

IRB	Institutional Review Board
JSON	JavaScript Object Notation
LAMP	Localized Aviation Model Output Statistics (MOS) Program
LCB	Lowest Cloud Base
LIFR	Low Instrument Flight Rules
LLWS	Low Level Wind Shear
LOC	Loss Of Control
METAR	Aviation Routine Weather Report
MDL	Meteorological Development Laboratory
MOS	Model Output Statistics
MSL	Mean Sea Level
MVFR	Marginal Visual Flight Rules
MWT	Mountain Wave Turbulence
NAIPS	National Aeronautical Information Processing System
NAS	National Airspace System
NASR	National Airspace System Resource
NAVAID	Navigation Aid
NBM	National Blend of Models
NCEP	National Centers for Environmental Prediction
NCO	NCEP Central Operations
NDFD	National Digital Forecast Database
NEXRAD	Next Generation Weather Radar
NOAA	National Oceanic and Atmospheric Administration

NOMADS	NOAA Operational Model Archive and Distribution System
NTSB	National Transportation Safety Board
NWP	Numerical Weather Prediction
NWS	National Weather Service
PAVE	Pilot, Aircraft, Environment and External Pressures
PIC	Pilot in Command
PIREP	Pilot Weather Report
POH	Pilot Operating Handbook
PWA	Progressive Web App
QPF	Quantitative Precipitation Forecast
RAP	Rapid Refresh
SID	Standard Instrument Departure
SLD	Supercooled Large Drop
SLW	Supercooled Liquid Water
SM	Statute Miles
SOP	Standard Operating Procedure
STAR	Standard Terminal Arrival Routes
TAF	Terminal Aerodrome Forecast
TAS	True Airspeed
TWEB	Transcribed Weather Broadcast
UNCC	University of North Carolina at Charlotte
UTC	Coordinated Universal Time
VFR	Visual Flight Rules

VMC	Visual Meteorological Conditions
WFO	Weather Forecast Office
WMO	World Meteorological Organization

CHAPTER 1: INTRODUCTION

"Once the validity of this mode of thought has been recognized, the final results appear almost simple; any intelligent undergraduate can understand them without much trouble. But the years of searching in the dark for a truth that one feels, but cannot express; the intense desire and the alternations of confidence and misgiving, until one breaks through to clarity and understanding, are only known to him who has himself experienced them."

- Albert Einstein, 1933

General aviation (GA) pilots in the United States face a difficult technical challenge when planning an upcoming cross-country flight[1]. With respect to weather, some flights are more challenging than others. Adverse weather affects all GA pilots, but especially vulnerable are those pilots flying light fixed-wing aircraft and helicopters. While a small subset of these are high-performance[2] pressurized aircraft that are capable of flying at altitudes exceeding 25,000 feet above mean sea level (MSL), most are low performance aircraft and fly at lower altitudes (i.e., below 15,000 feet MSL) where exposure to hazardous weather is much more common (Li & Baker, 2007).

The weather-related GA accident rate has stagnated over the last two decades. This is in stark contrast to the fact that availability of weather reports and forecasts has vastly improved given the wide variety of unfettered weather guidance now available online. Moreover, pilots now have timely access to weather reports and forecasts while in flight through affordable satellite and ground-based systems that broadcast a subset of the latest weather to receivers in the cockpit and are displayed on multifunction displays and/or portable electronic devices such as an iPad. Despite these advancements in technology, weather remains an obstacle for GA pilots

[1] A cross-country flight is defined by FAA regulations as a flight that includes a landing at a point other than the point of departure, independent of the distance flown.
[2] High-performance is defined by FAA regulations as an airplane with an engine capable of developing more than 200 horsepower.

(Fultz & Ashley, 2016). So it would seem that weather-related accidents should continue to decline as availability to high spatiotemporal weather guidance has become ubiquitous.

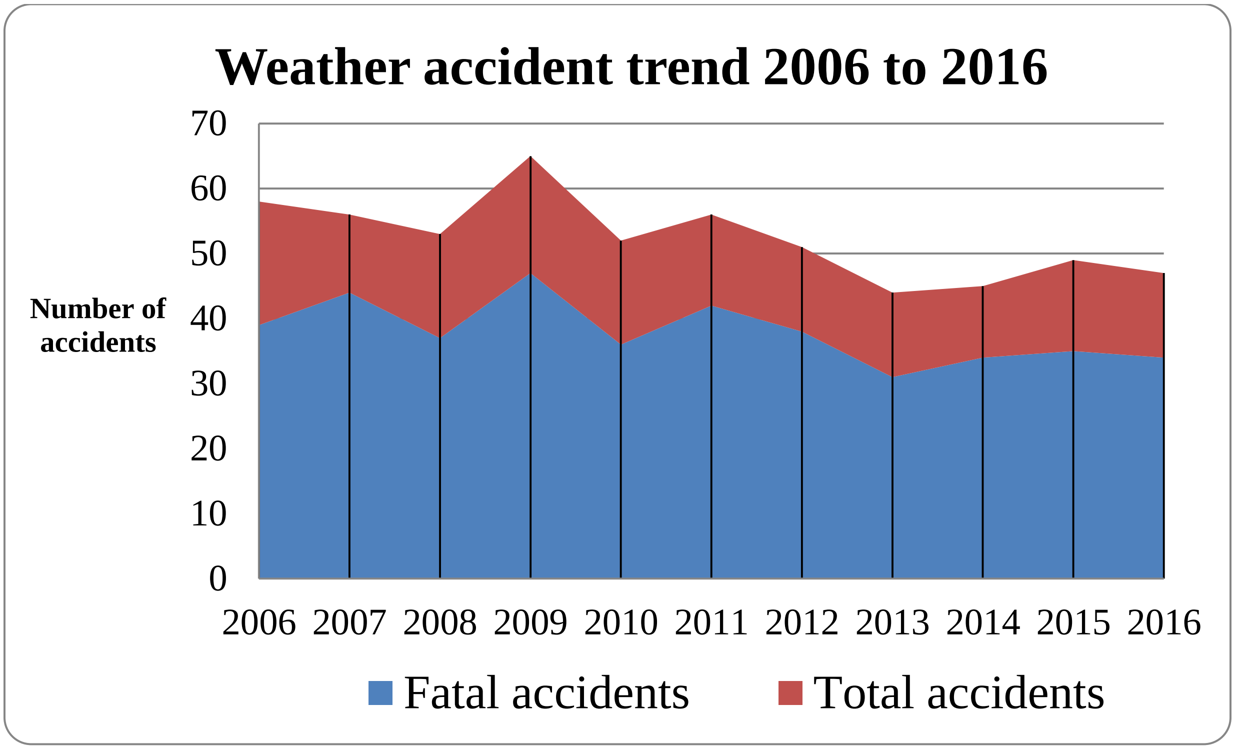


Figure 1. General aviation weather-related fatal and nonfatal accident trend not associated with wind from 2006 to 2016 (AOPA, 2018).

The most common causal or contributing factors reported by the Federal Aviation Administration (FAA) and the National Transportation Safety Board (NTSB) for weather-related fatal and nonfatal accidents in no specific order are (1) wind, (2) convective weather, (3) turbulence, (4) temperature, humidity, and pressure, and (5) ceiling, visibility, and precipitation (NTSB, 2010). While not all encounters with hazardous weather result in fatalities, many accidents or incidents include serious injury to the pilot and/or passengers and in rare cases to innocent bystanders on the ground. Furthermore, aircraft or property can be damaged, sometimes beyond repair. The overall effect of these accidents leads to 100 fatalities to crew and/or passengers every year in the United States (Fultz & Ashley, 2016). Considering weather, the period from 2006 to 2016 suggests (Figure 1) little or no reduction in fatal and nonfatal weather-related accidents (AOPA, 2018).

Pilots flying under Visual Flight Rules (VFR) face an even greater challenge. Outside of wind-related accidents, VFR flights into instrument meteorological conditions (IMC) or “VFR into IMC” remains the number one cause of weather-related accidents (AOPA, 2018). Instrument meteorological conditions define a flight environment whereby operating an aircraft solely by visual references located outside of the cockpit are highly restricted or no longer available (Fultz & Ashley, 2016). More importantly, VFR into IMC accidents are the most deadly when looking at all of the causal factors related to weather (AOPA, 2018). For example, in 2015 there were 21 accidents (Figure 2) attributed to VFR into IMC. Twenty of those accidents resulted in fatalities of the pilot and/or passengers in the aircraft (AOPA, 2018). A notable recent helicopter crash which led to the death of National Basketball Association legend Kobe Bryant on January 26, 2020 was determined by the NTSB to be “the pilot’s decision to continue flight under visual flight rules into instrument meteorological conditions,” leading to “spatial disorientation and loss of control.” Loss of control (LOC) or controlled flight into terrain[3] (CFIT) is quite common with accidents where the primary causal factor is attributed to VFR into IMC (Johnson & Wiegmann, 2015). Many of these accidents are highly avoidable given the right weather guidance and the recognition of the risk of adverse weather along the proposed route of flight.

[3] Terrain in this case also considers radio towers, moored balloons, wind turbines and other human-made obstructions.

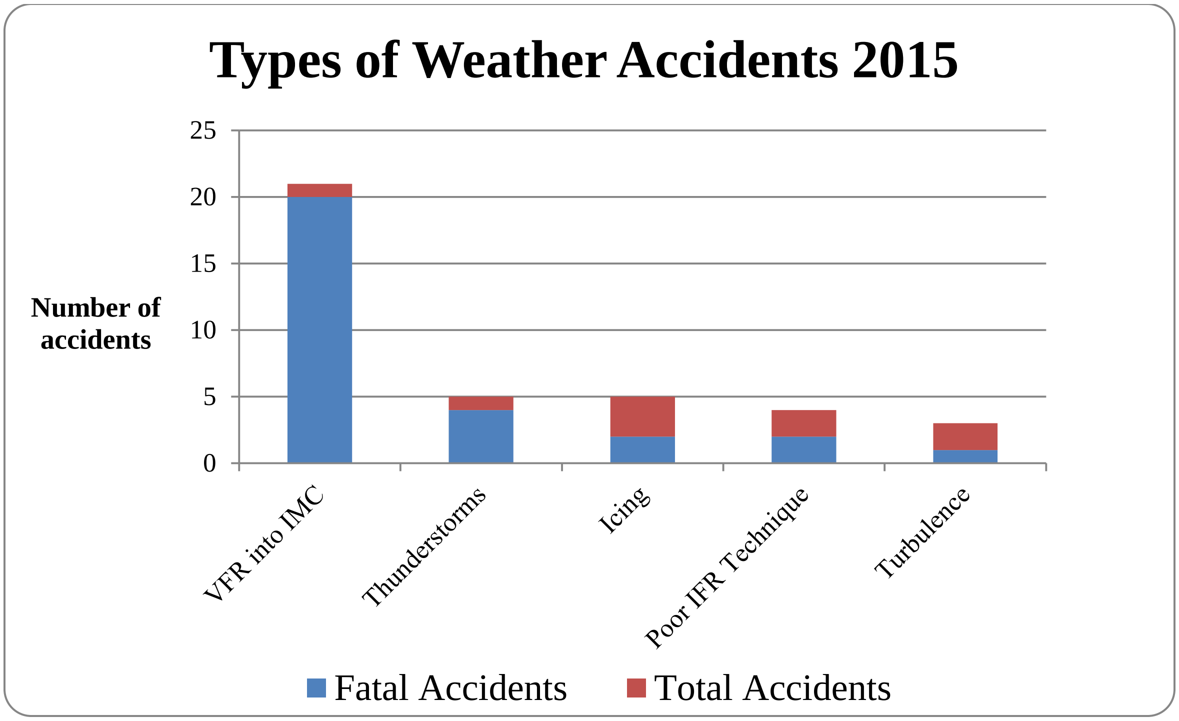


Figure 2. Weather-related fatal and nonfatal accidents not associated with wind for 2015 based on type of accident (AOPA, 2018).

The "stagnant weather-related accident rate" may be attributed to several factors that include insufficient preflight analysis and lack of aviation weather knowledge (King et al., 2019). Given that weather is highly variable on any given day, preflight weather planning requires pilots to acquire the weather information and interpret the results to a meaningful conclusion and this expectation has inherent risk to be associated with inappropriate or poor weather-related decision-making (Hunter, et al., 2011).

The FAA gives the pilot the final authority on the operation of the aircraft which includes preflight weather planning (Speciale & Venhuizen, 2007). However, many aviation accidents are highly preventable and often the result of a chain of poor decisions and human error including those related to inadvertent flight into IMC (Jensen, 1982). Pilots must rely on weather forecasts that are inherently imperfect. Poor forecasts are cited in the literature as the cause of some of the weather-related accidents, but they are not likely the underlying reason pilots find themselves inadvertently encountering adverse weather during flight. A common contributor to these fatal accidents is the pilot’s inability to definitively assess the hazard prior to departure from the relevant weather guidance available (Blickensderfer et al., 2017). Therefore, it is hypothesized in this research that the lack of sufficient weather reports and forecasts and their accuracy are not the core concern, but instead the primary contributing factor is the way GA pilots consume the forecast guidance to develop a flight plan prior as a precursor to making a decision to fly.

Even though high spatiotemporal weather forecasts are now more robust and have become increasingly ubiquitous online, it is thought that pilots are not utilizing all of this information to their advantage. A GA pilot is not a trained meteorologist and often has a difficult time distilling all of the available information to make good preflight and inflight decisions (Blickensderfer, et al., 2017). Weather is quite complex, and pilots tend to prefer an easy solution (e.g., make a quick phone call to a briefer) to get their weather information (Knecht, 2007). Much of the weather guidance used to make an informed decision to fly is spread over many different and sometimes complex charts, diagrams and textual reports. As such, pilots often do not have a comprehensive approach that seamlessly integrates in time and space all of the pertinent weather guidance to make it obvious if they will encounter adverse weather along a proposed route of flight. It has become apparent that pilots need a well-integrated route-based application that simplifies and organizes this weather guidance in a way that requires less technical interpretation and gives time-based choices to minimize a pilot’s exposure to adverse weather. Consequently, a targeted software application represents a major opportunity to eliminate or significantly reduce the risk for human error especially as it relates to flights conducted under VFR.

This requires a novel approach that utilizes time as a key variable in order to optimize the best time to depart that clearly minimizes exposure to adverse weather. A GA pilot often has a flexible schedule and this creates an opportunity to leverage this organically. Consequently, they are more likely to choose a departure time with a lower overall risk when provided with multiple options that quantify and depict that risk in an easy to interpret way. Using an automated approach, this research also aims to optimize, assemble and display the most relevant weather guidance to increase the pilot's situational awareness with respect to adverse weather along their proposed route of flight. Building on existing high spatiotemporal resolution digital weather reports and forecasts, this research also asks: To what extent do a pilot's individual personal weather minimums weigh into their decision to fly and how can they be integrated into this automated approach? In this context, personal minimums allow the pilot to further tailor, quantify and acknowledge the risk they are willing to assume, thus adding a margin of safety based on a set of criteria coupled with their own self-analysis and level of flight experience. In this case, "minimums" reference the "minimum acceptable weather conditions" at an airport or along a route of flight.

Based on a review of the literature, including accident data, and a pilot survey, a standard set of personal weather minimums has been developed and categorized based on key adverse weather conditions cited as causal factors in both fatal and nonfatal weather-related accidents. Furthermore, using readily available information, appropriate weather reports and forecasts have been identified and used to distinguish, measure, and plot when adverse weather is possible along a route and at airports. The relevant weather is evaluated based on the pilot's individual set of personal weather minimums to provide an automated assessment of risk for a given set of hourly departure times over a 2-3-day period.

The product of the research is an automated online weather decision support tool that analyzes the key weather variables critical for aviation and provides the results graphically in an easy-to-consume depiction that has a high glance value. The results of the evaluation is quantified using a simple traffic light concept; namely green, yellow and red, whereby each personal weather minimum category is evaluated at the airport and along the route of flight based on the forecast weather available for a specific time of departure. Green is used by the pilot to define a very conservative threshold. When the forecast weather is equal to or better than this threshold, the flight risk from a weather perspective is deemed by the pilot to be negligible. Red, on the other hand, is at the other extreme. Red defines the pilot's actual personal weather minimums. That is, if the forecast weather is the same or worse than this threshold, the flight risk is deemed by the pilot to have a high risk based on these minimums. Lastly, yellow advises the pilot to exercise caution. In this case, the forecast weather is better than the pilot's personal weather minimums (i.e., red), but worse than the conservative threshold (i.e., green). Consequently, yellow is deemed to be of moderate risk as the weather is forecast to approach the pilot's personal weather minimums. Of course, the pilot can set the thresholds in such a way that there is little or no moderate risk to evaluate. The key goal is to evaluate the weather along the proposed route for each personal weather minimum category for all possible departure times over the next 2-3-day period. A pilot can use this decision support tool to quickly assess the most appropriate time to depart that meets all of their personal minimums, and thus, minimizes their exposure to adverse weather.

CHAPTER 2: LITERATURE REVIEW

Published studies that focused on any adverse weather hazard and the risk to GA pilots were consulted; however, studies that focused on VFR into IMC in the United States in the GA segment were primarily selected for further analysis. The primary focus areas were related to the attitude, characteristics, behavior, and psychological disposition of the pilot when making a decision to progress from VFR into IMC and the preflight planning leading up to a departure that places the flight at risk of sustaining a weather-related accident. Current strategies to prevent occurrences of incidents and accidents and the role of the pilot in this connection were explored. Furthermore, the importance of personal weather minimums was of special concern to determine how these may enhance safety. The main findings and inferences of the review are included in the sections that follow.

According to a 2019 Aircraft Owners and Pilots Association (AOPA) report of the state of general aviation (GA), there are ~609,000 certificated pilots in the United States and 80% of those pilots fly civil aircraft registered in the United States (AOPA, 2019). While the total number of active pilots has decreased over the last decade, the number of hours flown and fuel consumption has largely remained constant or slightly increased in recent years (AOPA, 2019). According to the report, in 2017, “the number of aircraft handled by air traffic control (ATC) was up nearly 2% and the number of hours flown was up more than 2%.” Essentially there are less GA pilots flying, but those pilots are flying more often (AOPA, 2019).

2.1 Flight rules

For the purposes of this research, GA includes pilots flying civilian aircraft under the Code of Federal Regulations (CFR) Part 91 for personal and business travel, medical transport, aerial law enforcement, sightseeing, pipeline patrol, agricultural aviation, search and rescue, recreational flying and flight training among others (Fultz & Ashley, 2016). It does not include military flights or scheduled air carriers (e.g., United Airlines) flying under CFR Part 135 and Part 121, respectively. Given that over 97% of all civil aviation accidents are associated with GA flights (Boyd and Guinn, 2019) the focus of this research is on GA operations and its relatively poor safety record.

Furthermore, flights in the United States are conducted under two specific FAA rules, namely, visual flight rules (VFR) or instrument flight rules (IFR). VFR refers to specific aviation regulations that require a pilot to control the navigation, attitude, and obstacle avoidance (e.g., separation from other aircraft and terrain) of the aircraft independently in weather conditions that allow for visual references and positive aircraft control. VFR requires pilots to adhere to strict rules such as maintaining certain distance from clouds, flight visibility, and ceiling height in accordance with regulatory minimums depending on the airspace occupied (Skybrary, 2017). For pilots flying under VFR, the primary threats are low ceiling height, fog and/or reduced surface visibility or mountain obscuration (Herman & Schumacher, 2016). This is the result of clouds near the surface, surface-based obstructions such as haze, mist, precipitation, smoke or any combination of these. When these regulatory minimums cannot be satisfied, the pilot is expected to fly under IFR which requires the pilot to possess an instrument rating and the aircraft flown must be certified for instrument flight (Madhavan & Lacson, 2006).

2.2 Flight category

To better represent an IMC weather threat at airports, the National Weather Service (NWS) and FAA designate flight categories (Table 1). While they are loosely tied to the visual and instrument flight rules mentioned above, these categories are directly related to weather conditions and are not dependent on the airspace occupied by the flight. This combines the airport's ceiling[4] and surface visibility (forecast or observed) to produce the following four weather categories: (1) instrument flight rules (IFR); (2) low instrument flight rules (LIFR); (3) visual flight rules (VFR); and (4) marginal visual flight rules (MVFR) (Keller et al., 2014). For example, if the surface observation or forecast at the airport included a ceiling height of 1,100 feet and surface visibility of 2 statute miles, the airport's flight category is set as IFR due to the restricted surface visibility of 2 statute miles.

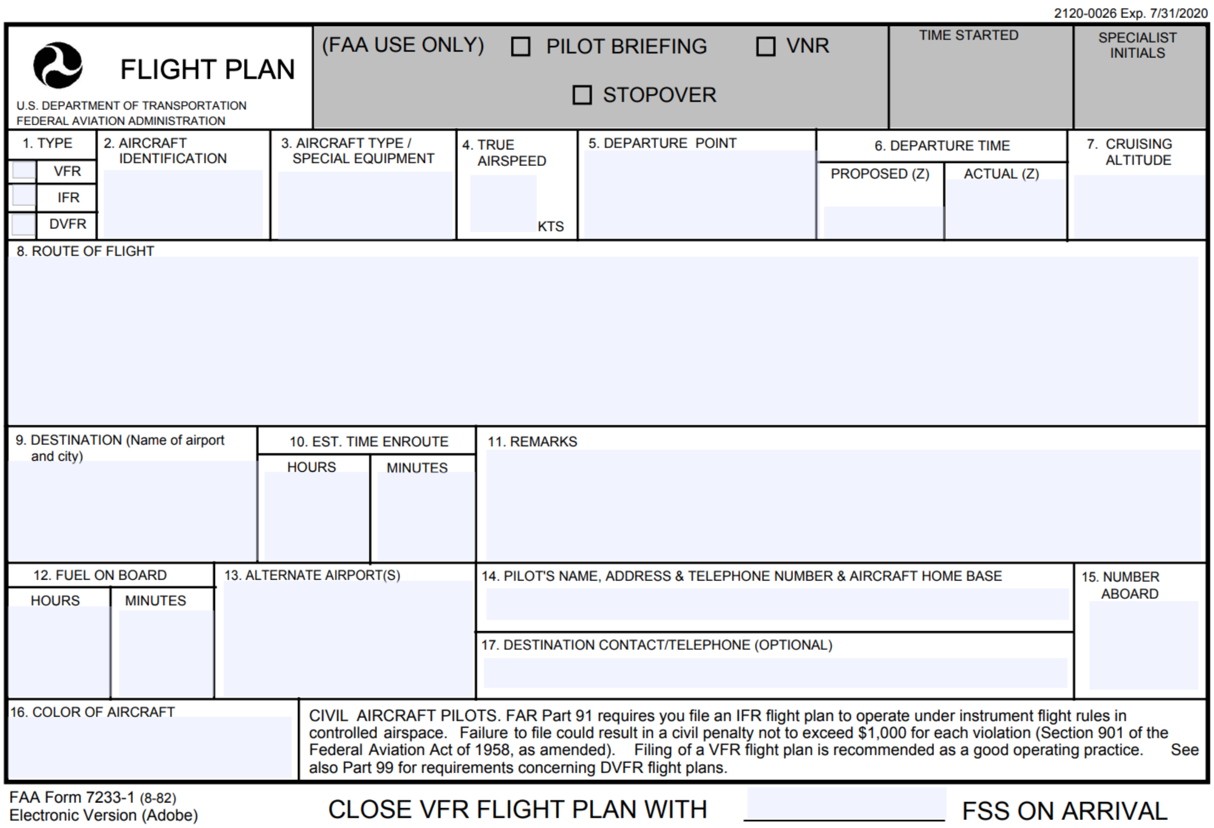
Table 1. Color-coded flight category definitions and based on ceiling height and surface visibility that include Low Instrument Flight Rules (LIFR), Instrument Flight Rules (IFR), Marginal Visual Flight Rules (MVFR) and Visual Flight Rules (VFR).

Flight Category	Ceiling height (AGL)		Surface visibility	Color used
LIFR	< 500 feet	or	< 1 statute mile	Magenta
IFR	500 – 900 feet	or	1 - < 3 statute miles	Red
MVFR	1000 – 3000 feet	or	3 – 5 statute miles	Blue
VFR	> 3000 feet	and	> 5 statute miles	Green

2.3 Briefing methodology

The FAA regulations require that each pilot in command (PIC) become familiar with weather reports and forecasts for that proposed flight (FAA, 2005). Non-regulatory FAA guidance encourages the PIC to use a telephone briefing service provided through an FAA contractor, colloquially referred to as "flight service," by calling a dedicated telephone number, namely, 1-800-WXBRIEF (NTSB, 2005). Although these flight service specialists are trained to brief pilots, there are no requirements for them to be a meteorologist. During the phone call the pilot provides the briefer flight plan information (Figure 3) to include the departure and destination airports, route of flight, planned altitude, duration of flight, estimated time of departure and other fields as necessary.

[4] A ceiling as defined by the FAA is the lowest overcast or broken cloud layer or vertical visibility into an obscuring phenomenon. Ceiling heights are measured relative to above ground level (AGL).



2120-0026 Exp. 7/31/2020

FLIGHT PLAN

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

(FAA USE ONLY) ☐ PILOT BRIEFING ☐ VNR

☐ STOPOVER

TIME STARTED

SPECIALIST INITIALS

1. TYPE — VFR, IFR, DVFR

2. AIRCRAFT IDENTIFICATION

3. AIRCRAFT TYPE / SPECIAL EQUIPMENT

4. TRUE AIRSPEED — KTS

5. DEPARTURE POINT

6. DEPARTURE TIME — PROPOSED (Z), ACTUAL (Z)

7. CRUISING ALTITUDE

8. ROUTE OF FLIGHT

9. DESTINATION (Name of airport and city)

10. EST. TIME ENROUTE — HOURS, MINUTES

11. REMARKS

12. FUEL ON BOARD — HOURS, MINUTES

13. ALTERNATE AIRPORT(S)

14. PILOT'S NAME, ADDRESS & TELEPHONE NUMBER & AIRCRAFT HOME BASE

15. NUMBER ABOARD

17. DESTINATION CONTACT/TELEPHONE (OPTIONAL)

16. COLOR OF AIRCRAFT

CIVIL AIRCRAFT PILOTS. FAR Part 91 requires you file an IFR flight plan to operate under instrument flight rules in controlled airspace. Failure to file could result in a civil penalty not to exceed $1,000 for each violation (Section 901 of the Federal Aviation Act of 1958, as amended). Filing of a VFR flight plan is recommended as a good operating practice. See also Part 99 for requirements concerning DVFR flight plans.

FAA Form 7233-1 (8-82)
Electronic Version (Adobe)

CLOSE VFR FLIGHT PLAN WITH ______________ FSS ON ARRIVAL

Figure 3. The simplified flight plan form, FAA Form 7233-1 available at https://www.faa.gov/documentLibrary/media/Form/FAA_Form_7233-1_7_31_17.pdf.

As directed in the Aviation Weather Services FAA Advisory Circular (AC) 00-45H, Change 2, during this call the briefer will read all of the official weather reports and forecasts to the pilot that are relevant to the proposed route (FAA, 2016). The briefer will also read the active advisories for airframe icing, turbulence, non-convective low level wind shear, strong surface winds, instrument flight rules (IFR) conditions, mountain obscuration, and convective potential that may impact the proposed route. While pertinent weather information is transferred to the pilot, verbalized reports given over the phone are not as productive as seeing a graphic of plotted weather along the proposed route (FAA, 2016). Moreover, pilots are not trained meteorologists and often have a difficult time distilling all of the available weather guidance to make good preflight decisions (Wilson & Sloan, 2003).

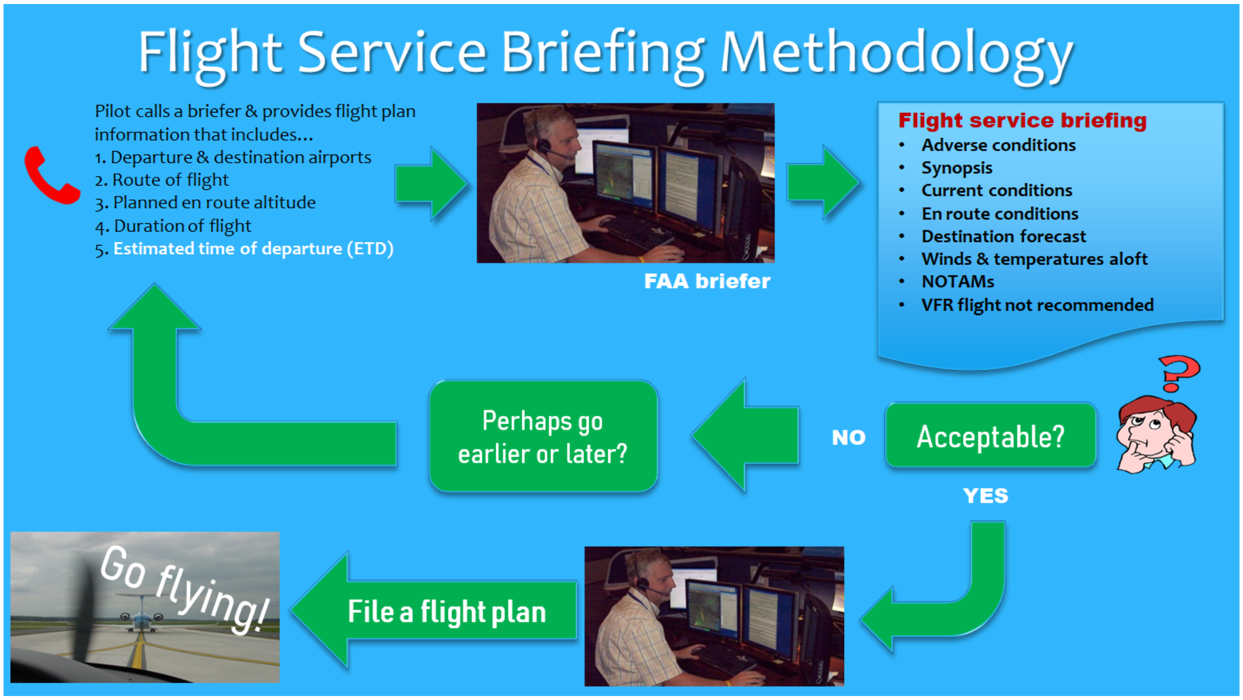


Figure 4. The FAA-recommended methodology used by GA pilots to get a preflight weather briefing through Flight Service.

The current standard weather briefing methodology (Figure 4) still encouraged by the FAA operates on the premise that a pilot has a fixed departure time since they are expected to file the appropriate flight plan based on this time. Consequently, the weather briefing is essentially anchored to this estimated time of departure. This means the briefing is not optimized based on other potential departure times that may allow a better opportunity to further minimize the pilot's exposure to adverse weather. Changing the departure time by a few hours or even a day may significantly lower the risk of encountering adverse weather. To depart at a different time often requires a complete reexamination of the route by the briefer. For departure times beyond six hours from when the pilot asks for a briefing, forces the briefer to change to an outlook briefing which carries more uncertainty and provides less detailed weather guidance (FAA, 2016). Moreover, a pilot's personal risks (also known as personal minimums) are not considered during this briefing process. The FAA outlines in the Aeronautical Information

Manual (AIM), advisory circulars and various handbooks, the multitude of information sources available to pilots for their pre-flight weather planning and analysis. However, Flight Service serves as a comprehensive source of weather information and Notices to Airmen (NOTAM). Official FAA weather products derive data from the National Weather Service (NWS) and other sources related to flight planning to provide pilots with specific and meaningful weather guidance.

2.4 Preflight briefing process

After obtaining the weather information, pilots must be able to successfully map the effects of current weather observations, forecast data, and official advisories to its impact on an upcoming flight. Nevertheless, studies have indicated that even though pilots receive preflight weather briefings, they did not give proper weight to the weather along the route, and therefore, did not expect IMC in their preflight analysis (Gallo et al., 2018).

The FAA recommends pilots use three basic steps during the preflight planning process: Perceive, Process and Perform (FAA, 2006). Preflight planning related to weather requires pilots to harvest guidance from many weather sources to develop a realistic plan of action to create a "mental model" that will assist them in their flight. In line with FAA recommendations, the preflight planning process must initiate the "perceive" step where pilots are expected to acquire weather information from a range of relevant sources. In addition to getting a Flight Service telephone briefing mentioned above, they are encouraged to consult various online resources and specialized aviation weather applications to augment the telephone briefing. To successfully acquire relevant and quality weather information, familiarity and usability of the information gathered is crucial.

The next step requires the pilot to “process” this information. During this step, pilots may be often limited by their own comprehension of foundational weather principles leading to inadequacy in interpreting weather information, distortion of the information, an inaccurate mental model, and possibly hazardous behavior (FAA, 2016). When assessing risk, for example, pilots sometimes use previous successful experiences in similar weather as a means to justify future flights. In other words, risk can be addictive. With respect to weather, this creates a hazardous attitude where pilots can often take a significant risk on one flight through adverse weather which leads them to take even more risk on subsequent flights. Moreover, outside pressures or a tight schedule can have a dominant effect on a pilot to overlook hazardous weather and make a hasty decision to depart (FAA, 2016).

As pilots progress to the “perform” step in the weather preflight planning process, they are expected to apply the weather information acquired so far to their upcoming flight. This stage poses the greatest number of challenges as pilots must be able to map weather conditions to their relevant flight safety risks along the proposed route of flight. Poor preflight planning may adversely affect inflight risk assessment and decision-making (King et al., 2019).

Typical supplemental weather data sources used by GA pilots include the Aviation Digital Data Service (ADDS)[5] from the Aviation Weather Center (AWC) that provides a web-based interface to various weather reports and forecasts. Several online decision support tools and apps are available to assist pilots in obtaining, understanding, and applying weather information. The major aspect that the tools are expected to address is related to supporting complicated tasks that require a high level of cognitive ability. Characteristics such as usability, automation, low level analysis, and expert knowledge are desirable for successfully determining risk, applying weather guidance, and establishing personal minimums (King et al., 2019).

[5] See https://aviationweather.gov.

However, an analysis of weather tools such as the electronic flight bag (EFB) applications (e.g., Garmin Pilot) and ADDS indicates that the data and its representations (station plots, satellite data, radar data, en route advisories and the like) have a low degree of interpretability among GA pilots (King et al., 2019). Researchers found that the incorporation of usability in the interface was critical to enhancing the interpretability of the weather product (King et al., 2018).

2.5 Weather training and skills

In many cases, pilots find it overwhelming to cope with the rapidly changing weather technologies available for extracting quality information. Besides predicting the effects of complex weather conditions, they also require a fair understanding of the strengths and weaknesses of currently available onboard systems and their displays (Blickensderfer et al., 2015). Even when GA pilots are adept with the interpretation of weather charts, they do not receive adequate practical exposure since the approaches used in primary training do not incorporate all effects related to weather, especially with respect to low flight visibility or low ceiling height (Berendschot et al., 2018).

The FAA maintains that preflight decision-making is a critical focus area for pilots (FAA, 2016). About 188,000 GA pilots operate in the U.S. airspace and certain basic skills improve the safety of the flying experience: proficiency in marginal weather, obtaining relevant weather information, reviewing weather personal minimums, developing a “personal safety buffer” based on “skills, training, currency, and proficiency”, and communicating with fellow-professionals about weather decision-making (Huerta, 2017). Experts recommend the inclusion of weather training in the flight instruction curriculum, with specific focus on simulations for VFR into IMC. The curriculum must incorporate strategies to avoid instances of inadvertent VFR into IMC. In addition, the causes of inadvertent VFR into IMC are not always clear, but may be identified through detailed research studies including approaches to measure pilot attitudes, and expand on the sample and demographic studied to obtain meaningful inferences (Goh & Wiegmann, 2001). From another perspective, current meteorological knowledge and weather prediction requires a transition to the next level entailing integrated systems that consolidate the parameters of turbulence, wind, visibility, ceiling, icing, precipitation, and convection to determine measurement thresholds for extreme adverse weather conditions. Statistical and deterministic approaches may be regarded as the mainstay for aviation forecasts in the future (Gultepe et al., 2019). In line with this view, the system offered in this dissertation discusses a solution that allows pilots to define personal minimums as a form of risk assessment and assists them in decision-making related to departure times by applying and integrating weather information through an automated web-based approach.

2.6 VFR into IMC accidents

Visual Flight Rules (VFR) refer to regulations in aviation that enable a pilot to control the navigation, attitude, and obstacle avoidance (such as other aircraft and terrain) of the aircraft independently in weather conditions that allow visual control. Visual meteorological conditions (VMC) refer to the minimum meteorological requirements for VFR such as maintaining certain distance from clouds, visibility, and ceiling in accordance with established minimums or a better value (Skybrary, 2017). When these conditions are not satisfied, the pilot is expected to fly under IFR (Madhavan & Lacson, 2006).

The NTSB and the FAA highlight that a large proportion of weather-related GA accidents which are either nonfatal or fatal occur as a result of several weather factors to include visibility, low ceiling height, wind and elevated density altitude (FAA, 2010). Weather has been listed as the main contributing factor or primary cause of 35% of GA accidents which occur annually in the United States (Fultz & Ashley, 2016). When looking at all GA accidents, 6% of them are due to VFR into IMC; however, they are responsible for a quarter of all GA accidents that result in a fatality (Groff & Price, 2006). NTSB data also reveals that out of all weather-related general aviation accidents, the highest number of GA fatalities occur when a pilot flies from VFR into IMC (AOPA, 2018). Inadvertent VFR into IMC often results in task saturation, spatial disorientation and loss of control (LOC). Controlled flight into terrain (CFIT) and LOC accidents account for a total of 75% of general aviation fatalities which are weather related (Gallo et al., 2018).

Although all pilots are prone to VFR into IMC accidents, pilots with less flight experience (mostly below 1,000 logged flight hours) have the highest propensity for such accidents (Wilson & Sloan, 2003). The significant threats facing VFR flights include reduced surface visibility, fog, low ceiling heights and mountain obscuration (Herman & Schumacher, 2016). While such threats may prove fatal to pilots flying under VFR, those pilots rated to fly solely by reference to instruments under IFR are less likely to succumb to this threat. This, however, is under the condition that the instrument rated pilot has met all of the training and recent flight experience required to fly in conditions of reduced visibility. Nevertheless, in spite of this advantage, poor IFR technique (Figure 2) has also been a cause of some nonfatal and fatal accidents (AOPA, 2018). As such, inadvertent VFR into IMC or poor IFR technique may still result in either CFIT or LOC (AOPA, 2018; Hunter, et al., 2011; Wilson & Sloan, 2003).

The discussion is mainly focused on VFR into IMC and the rationale behind developing an application that may assist GA pilots in determining personal weather minimums by providing the necessary decision making capability through data on other adverse weather phenomena such as turbulence, thunderstorms, and icing. The number of accidents related to weather is a fifth of the total occurrence and half of the accidents occur due to pilot's decision to continue into a VFR into IMC situation (Ison, 2014).

A vast majority of these accidents have the pilot error component. According to the Human Factors Analysis and Classification System (HFACS), a system used by FAA to identify causes of human error in incidents and accidents, four out of ten categories identifying causes are relevant to GA occurrences (Wiegman et al., 2005; Wiegmann & Shappell, 2017). These categories include violations, perceptual error (altitude, aircraft control, descent), skill-based error (altitude/clearance, clearance, aircraft control), and decision errors (weather decision, in-flight planning). According to NTSB data collected between 1990 and 1997, 2.5% of the 14,000 accidents were linked to VFR into IMC accounting for 11% fatalities (Ayiei et al., 2020).

Pilot characteristics observed in such occurrences were mainly a higher rating for skills and judgment, accompanied by a higher level of confidence with respect to aptitude in adverse circumstances. However, their positive self-perception still resulted in errors related to decision-making with the majority tied to inaccurate visibility assessment. Overconfidence while making decisions adversely affected the problem-solving ability and memory retrieval capacity, leading to task saturation and sub-optimal performance. Experts refer to the nature of this overconfidence as the "Dunning-Kruger" effect (Kruger & Dunning, 1999). From another perspective, pattern matching and recognition are important elements of perception and reflect the nature of training and experience. In another study, experts argued that VFR into IMC is the result of poor situational assessment and motivational factors or risk-taking behaviors may not contribute to the final decision. Their findings imply the need for developing superior weather skills in weather evaluation beyond addressing risk-taking attitudes (Wiegmann et al., 2002).

Quantitative studies have noted several conclusions related to VFR into IMC occurrences: the seriousness of such occurrences is more than expected; no reduction in the occurrence rate has been observed but efforts must be taken to reduce these occurrences; most occurrences were recorded by pilots with more than 500 hours of flying experience; and student pilots have a disproportionately higher rate (Ayiei et al., 2020; Boyd & Guinn, 2019; Gultepe et al., 2019; O'Connor & Kearney, 2019).

The breadth and depth of the problem is evident in the hundreds of fatalities associated with it. According to data from the NTSB, two-thirds of VFR into IMC accidents are fatal, a ratio that exceeds accidents caused by pilot incapacitation, mid-air collisions, and wire strikes (Gallo et al., 2018). The consequences and causes of VFR into IMC include misinterpretation of aircraft position, controlled flight into terrain (CFIT), disorientation and departure from controlled flight due to reduced visibility; loss of control of aircraft, in-flight structural failure, and unrecoverable flight attitude due to spatial disorientation (Ayiei et al., 2020).

2.7 Strategies to prevent incidents and accidents from weather hazards

Hazards from weather may be avoided if pilots perform certain tasks prior to and during their flight such as interpreting weather forecast and weather information as part of flight planning and making decisions based on it. Research evidence indicates that only a third (9 out of 26) of the incidents recorded had weather data from the National Aeronautical Information Processing System (NAIPS) incorporated into the flight planning (Ayiei et al., 2020). In the same study, failure to access aeronautical service for weather information was causal for seven fatalities (Ayiei et al., 2020). With regard to situational awareness, pilots must be able to understand the different aspects of their environment such as low visibility, recognize the prevailing situation such as visibility under VFR, and prediction of the future status such as if there is a chance of improvement in visibility and the possibility to continue towards the destination (Whitehurst et al., 2019).

The common consequences of continuing VFR into IMC include unrecoverable flight attitude, structural failure, or graveyard spiral as a result of spatial disorientation and LOC. In terms of preventing accidents and incidents due to adverse weather, a primary causal factor, VFR specifies that a minimum threshold for visibility and cloud clearance be maintained. Furthermore, inadvertent VFR into IMC by way of entry into fog or clouds is more common at night and accounts for one-third of the VFR into IMC accidents in the United States (Wilson & Sloan, 2003). Certain investigators argue that there are inherent limitations with regard to human perceptions of depth and distance, making it difficult to assess the possibility of inadvertent VFR into IMC (Wilson & Sloan, 2003). The result is apparent in terms of pilots' tendency to overfly their visibility when navigating in reduced visibility conditions and the phenomenon of aerial perspective where pilots tend to overestimate distances as visibility is limited.

Several approaches have been explored in the past few years to reduce the occurrence of incidences and accidents as a result of inadvertent VFR into IMC. Simple strategies to enforce recognition of hazardous weather and make prudent decisions may include one-on-one group discussions, computer-based training (CBT), and exercises on pencil and paper (Wilson & Sloan, 2003). Another important strategy is cue-based training, where cues are used to guide decision-making. Using the cue-based approach, expert pilots are first prompted to environmental cues of degrading conditions. Using this information, participants are expected to make judgments pertaining to inflight weather conditions. To incorporate a realistic scenario, the pilots are provided with a restricted time frame of 10 seconds to accomplish their decision-making process.

On self-evaluation, pilots who participated in the technique found it useful for application to real-world scenarios. Results indicated that the technique had the potential to respond effectively to faults inherent in complex systems, which may be either large-scale failures or faults with a lesser degree of complexity. The system relies on establishing links between cues that relate to specific situations and references in long-term memory. Such systems have the potential to enhance cognitive skills for a better recognition and diagnosis of faults. Moreover, the system is cost-effective at the individual as well as group levels (Wiggins & O'Hare, 2003).

The FAA proposed a five-year plan targeting the safety of GA through the implementation of safety promotion, risk management, training, and outreach and engagement. Effective risk management entails identifying and mitigating risk, through industry collaboration and scrutiny of accident data to discern risk patterns (Keller et al., 2014). Experiential education (ExpEd) is an integral part of FAA Weather technology in the Cockpit research project which provides simulation-based training on hazardous weather experiences that the pilot is likely to encounter under VFR. The modules are delivered over the web and particularly useful to GA pilots due to their accessibility and applicability to non-instrument certified pilots. Web-based modules proved to be more effective than video modules since they were interactive and capable of delivering complex material. Whitehurst et al. (2019) describe ExpEd module for estimating visibility to promote situational awareness and enhance decision-making capabilities of GA pilots. The program is based on providing "visual experiences of deteriorating weather". Pilots received preflight briefing on route, aircraft, and forecasted as well as actual weather of the destination, departure, and en route airfields. They were also briefed about the simulator configured according to the "Mooney Bravo single-engine aircraft with the G1000 type GA glass cockpit control display" (Whitehurst et al., 2019).

Preflight weather briefings are the first link in the accident chain preventing incidents and accidents for GA pilots. Towards this end, common techniques include aviation routine weather reports (METARs), and surface analyses and prognostic or “prog” charts. The common aerodrome-specific tools used by pilots for GA flight planning include Localized Aviation Model Output Statistics (MOS) Program (LAMP) and Terminal Aerodrome Forecast (TAF). According to the FAA, LAMP is recommended as a supplementary tool to TAF. Unlike the TAF which is issued by NWS forecasters, LAMP is an automated forecast that depends on output from Global Forecast System (GFS) MOS and other meteorological data. Certain experts argue that LAMP serves as a more accurate forecast tool when compared to TAF (Boyd & Guinn, 2019). The LAMP also provides an airport-specific forecast for more than three times the number of airports than does a TAF (Ghirardelli & Glahn, 2011). This opens up an aviation-specific forecast for more public-use GA airports.

While forecast tools are important in the mitigation of weather-based accidents, the current measures used for the purpose of reducing weather-related accident risk include: (1) the identification of major hazards, risk factors, and standard operating procedures and (2) the assessment of the correlation between various identified factors and accident risk (Howell & King, 2019). In addition to these measures, the integration of refresher training and thorough flight planning also serve the purpose of reducing the risk of weather-related accidents. It should be noted that once a private pilot earns their certificate there are no specific continuing education requirements that specifically call out weather as a topic of further discussion. While refresher training is not required by the FAA, various flight courses on convection and icing offered in the spring and winter, respectively, ensure that the pilots are able to plan for and navigate different forms of weather.

2.8 The importance of pilot adherence to personal weather minimums

In addition to the aforementioned measures used to assess the risk of weather-related accidents, the examination of personal minimums for pilots also plays a major role in identifying and assessing potential accident risks. Personal minimums have been defined by Ruiz (2018) as the minimum conditions which are necessary to ensure flight safety. These conditions encompass the set of criteria, rules, guidelines and procedures used by pilots to help them decide on the conditions and circumstances under which they can continue or begin operating a flight within the U.S. National Airspace System. Some of the criteria involved in the determination of personal minimums include: pilot's health, aeronautical ratings, flying experience and weather. In order to facilitate the process of setting personal minimums for GA pilots, the PAVE acronym can be utilized. This acronym has been recognized as the industry standard for setting personal minimums within the U.S. aviation sector (Ruiz, 2018).

According to Ruiz (2001), the PAVE acronym stands for **P**ilot, **A**ircraft, en**V**ironment and **E**xternal pressures. Each category within the acronym involves a number of questions which aid pilots in determining their personal minimums. For instance, while questions in the Pilot category assess the pilot's health, physical condition, mental condition, piloting skills, aircraft operation skills and level of aircraft-specialized training, those in the Aircraft category assess the aircraft's flight-worthiness, maintenance history, fuel level and preflight inspection program (Ruiz, 2018). Similarly, while questions in the environment category aid the analysis of weather conditions which are expected and the availability of alternative airports in case of emergencies during flight, questions in the external pressures category aid in the analysis of flight completion time and its relation to the pilot's pressure to complete the flight on time owing to constraints set by passengers and other commitments after the flight.

While personal minimums are not a requirement for pilots before beginning a flight, they still play a major role in enabling the setting of minimum thresholds or limits by pilots, in a way which allows for the integration of higher levels of conservativeness and objectiveness within the preflight decision-making process. In turn, this lowers the accident risk facing any GA flight, while taking into account the risk tolerance, experience and ratings of the pilot. As such, the quantification and evaluation of risks involved in various weather-based flight aspects therefore becomes possible through the use of personal minimums. Consequently, personal minimums are set with the goal of applying a set of defined thresholds to analyze the prevailing flight conditions and alert the pilot upon the discovery of potentially hazardous variables. The determination of personal minimums according to the FAA criterion, more specifically through the pilot and environment assessment categories, can also be integrated into the development of a weather assessment guidance system. This guidance system would facilitate the pilot's decision-making process by allowing them to make preflight weather-based decisions using a combination of weather data and their personal minimums, thus reducing the occurrence of VFR and IMC accidents by enabling the establishment of more conservative limits.

Adherence to personal weather minimums is a strategy for risk mitigation and enhances the decision-making capacity of the pilot. To understand the nature of this adherence, an experimental approach was assumed by Winter et al. (2020) to study the behavior of 112 pilots. Their study assessed how far pilots adhered to their personal weather minimums on conducting the flight, especially in the case of external pressures. When trainers and researchers simulated meteorological conditions that made it unsafe or illegal to make a landing, they observed that 96.4% of the pilots engaged in the study descended below their predetermined personal weather minimums and 81.5% descended below the minimum legal altitude published by the FAA. Their study confirmed that non-compliance with personal weather minimums cancel out the risk mitigation provided by the approach and make pilots susceptible to a higher level of risk (Winter et al., 2020).

2.9 Summary of key points

General aviation (GA) pilots in the United States have a difficult task when planning cross-country flights when faced with challenging weather along their route of flight. This is especially the case for GA pilots who fly light fixed-wing aircraft and helicopters. While the availability and accuracy of weather reports and forecasts has increased greatly over the past two decades, the number of weather-related accidents has remained stagnant. Fatal and nonfatal accidents are associated with adverse weather such as strong and gusty surface winds, airframe icing, turbulence, reduced visibility, low ceilings, high density altitude and thunderstorms. In the United States pilots flying VFR face the highest risk of weather-related accidents. Most important are VFR into IMC accidents which has been proven to have the highest level of fatality among all weather-related accidents.

A significant number of these accidents occur as a result of pilot error when analyzing the weather prior to the flight. Given the increased online availability of weather reports and forecasts in recent years, pilots still have difficulty integrating all of this complex weather guidance to make informed weather decisions as to the route, altitude and timing of a departure. This is, in part, due to the lack of meteorological training among GA pilots which further complicates the decision. Moreover, a primary contributing factor is the way pilots consume the forecast guidance to develop a flight plan prior to making a decision to fly. The current briefing process used by pilots is antiquated and cumbersome and does little to optimize the best time to depart. To that end, pilots need a route-based approach that requires less technical weather interpretation and one gives time-based options that minimize the pilot's exposure to adverse weather. An automated software application would play a major role in reducing or eliminating weather-related accidents among GA fixed-wing light aircraft and helicopter pilots, specifically those operating under VFR.

Additionally, a pilot's individual personal weather minimums can enter into their decision to fly as a method to further quantify and acknowledge the risk they are willing to assume. Personal weather minimums add an extra margin of safety by establishing more conservative limits in an attempt to lower the flight risk, thus reducing the occurrence of weather-related accidents, especially those associated with VFR flight into IMC.

CHAPTER 3: STATEMENT OF HYPOTHESIS AND GOALS

3.1 Hypotheses

Aircraft accidents attributed to weather are, in large part, a direct result of the way general aviation pilots consume pre-flight weather guidance in an effort to develop a plan that minimizes their exposure to dangerous adverse weather. A route-based automated approach using personal weather minimum thresholds and a time-leveraged evaluation creates an opportunity for greatly improved pre-flight analysis and in-flight decision-making, thereby reducing the probability of injury and fatality due to the inherent complexities and shortcomings in current weather briefing process.

3.2 Goals

Develop a targeted web-based application that enables general aviation pilots flying light fixed-wing aircraft and helicopters to assess personal flight risk associated with adverse weather for a proposed route of flight by:

1. Developing a set of airport and route-based personal weather minimum categories that are consistent with the key causative factors of weather-related general aviation aircraft accidents, especially those accidents associated with VFR into IMC.
2. Developing an automated approach that uses the pilot’s personal weather minimums to evaluate adverse weather along a pilot’s proposed route of flight.
3. Depicting the results using an intuitive color-coded system (inspired by the traffic-light concept) and other route-based visual weather displays to quantify a pilot’s personal flight risk that also enables the pilot to choose a departure time over a two-day to three-day period that exhibits the lowest overall risk for a proposed route.

3.3 Target Audience

The primary target for this research is GA pilots flying light fixed-wing aircraft and helicopters in the United States. The research is not intended to be utilized by the military or scheduled air carriers (e.g., airlines) or commercial air charters.

CHAPTER 4: DATA AND METHODS

United States GA pilots often come across technical-based challenges during the planning process for cross-country flights. In particular, adverse weather poses a major challenge to GA pilots who are flying helicopters and light fixed-wing aircraft, thus exposing them to increased chances of weather-related incidents and accidents. While the availability of weather forecasts and reports has increased greatly over the past two decades thus improving the available weather guidance for aviation, the number of weather-related accidents has not yet showcased a commensurate reduction. According to the NTSB and the FAA, nonfatal and fatal accidents which are weather-related are frequently associated with convective low level wind shear, strong and gusty surface winds, airframe icing, turbulence, reduced visibility and low ceilings. More specifically, pilots who are flying under VFR have been reported to face the highest risk of weather-related accidents in the United States (AOPA, 2018). In addition to having the highest occurrence of risk, VFR into IMC accidents has also been proven to have the highest level of fatality among all weather-related accidents (AOPA, 2018).

While no definitive method exists to aid in the determination of the main reasons why fatal VFR into IMC accidents occur, a high number of these accidents occur as a result of pilot error during the process of pre-flight weather analysis, which leads to the use of inaccurate judgements on the level of safety of flight during specific weather conditions (AOPA, 2018). In addition, while poor and inaccurate weather forecasts have also been cited as one of the leading causes of weather-related accidents, they may not greatly factor in the inadvertent encounter of adverse weather by pilots flying under VFR. As such, this research therefore hypothesizes that although they are primary contributing factors, inaccurate weather reports are not core issues which contribute towards weather-related accidents, as compared to pilot analysis and decision-making. In spite of the overall improved ubiquity of this guidance, pilots still portray low levels of utilization for this technology when making pre-flight weather decisions. The reason behind this may be the lack of meteorological training among GA pilots, which further increases the complexity of finding the correct information necessary for flight within the vast amounts of weather guidance available. Although most of the data required to make accurate flight decisions is available within the online weather forecasts platforms, most of this data is dispersed among a variety of highly complex textual reports, diagrams and charts. Consequently, this indicates the absence of a comprehensive approach which would result in a seamless space and time integration of all available weather guidance data with the aim of developing an accurate assessment of the risk involved during a specific flight. In this light, it is therefore evident that pilots require a route-based application which is integrated into the aviation “system” for the purpose of organizing and simplifying weather-based data in a way which yields risk-minimizing options and requires less technical interpretation. This software application would play a major role in reducing or eliminating the risk of accidents among GA fixed-wing light aircraft and helicopter pilots, specifically those operating under VFR.

4.1 Personal minimum surveys

As such, this study developed a standard set of personal weather minimum for pilots through the use of a pilot survey and data obtained from a review of literature which revolves around weather-based aviation accidents in the United States. Upon their development, personal minimums were categorized on the basis of weather conditions which have been cited as key causative factors in nonfatal and fatal weather-related accidents. Moreover, the available weather guidance which provides the means of identifying hazardous weather along a proposed route of flight during pre-flight planning within United States was identified.

As outlined by the FAA, personal minimums are specific guidelines which allow for the exercise of safety by pilots within expectations which exceed or match the guidelines and rules which have been set for the purpose of upholding flight safety (Kirkbride et al., 1996). In addition, the establishment of personal minimums is often done on the basis of upholding a higher level of conservativeness than that which is reiterated by official non-regulatory and regulatory guidance systems (Jensen et al., 1996). In spite of them not being a newly developed concept within GA, military or commercial aviation, personal minimums provide a way for pilots to utilize a given criteria set for the analysis of the risk involved during a particular flight (Clausing, 1990). Although this research will focus on weather-related criteria, personal minimums can involve elements which include the pilot's physical and mental health, aeronautical ratings, flying experience, number of flight hours logged within a specific aircraft or time, flight length and the rules of flight. While a number of the specified criteria may require subjective evaluation, weather-related thresholds offer quantifiable objective-based analysis or evaluation, with the goal of obtaining an approach which is disciplined enough to not only minimize the level of risk involved, but to also create an alert for the pilot, warning against a situation which could prove to be potentially hazardous before flight (Ruiz, 2001). Nevertheless, in spite of its significant contribution to overall flight safety, the conduct of such an assessment by pilots still remains optional.

The presentation of personal minimums often takes place in the form of a checklist which requires a pilot's evaluation of the given criteria based on a specific scale provided. Use of checklists is a concept which is already included in primary pilot training programs.

Consequently, this implies that such checklists are not a new concept, thus meaning that they normally receive a high level of acceptance among pilots as a part of the normal pre-flight procedure. Nevertheless, in spite of this general acceptance, no accepted industry standards of official guidelines exist on the process of constructing checklists for personal minimums (Kirkbride et al., 1996). As such, a variety of checklist construction processes which have a wide range of complexity exist.

In addition to checklists currently used by all pilots, formulation of survey questions will also depend on variables identified for quantification of weather-related accident risk. Some of the variables included within the formulation of personal minimums include: visibility at departure, icing intensity, turbulence intensity, ceiling and the convective potential for the expected en route weather.

According to Knecht, Harris & Shappell (2005), departure visibility plays an important role in aircraft taxi and during situations such as initial climb and take off. During preflight preparation, analysis of the ceiling expected at the destination can be useful in determining the level of risk which will be encountered during approach and landing. While low ceilings may not have a major effect on IFR pilots flying high performance and technically-advanced aircraft, VFR pilots flying light fixed-wing aircraft and helicopters may encounter increased risk of weather-related accidents upon departure.

Airframe icing and its intensity is another crucial factor which is taken into account during preflight preparation. Icing is possible when supercooled liquid water (SLW) in the atmosphere freezes onto aircraft surfaces (e.g., wings and horizontal stabilizer) causing a disfiguring of the airfoil. If not removed, the aircraft can stall creating a LOC situation. Most pilots of light fixed-wing aircraft and helicopters are not certified to fly into known icing conditions. As such, while light icing conditions may not be considered to be a major threat to flight safety, moderate and heavy icing intensities may introduce the need for aircraft route adjustment for the purpose of avoiding an encounter with hazardous airframe icing. Moreover, many light fixed-wing aircraft and helicopters do not have certified ice protection systems and flight into known icing conditions is prohibited based on FAA regulations.

Turbulence intensity, much like icing intensity, plays a major role in the assessment of flight safety. While light and moderate turbulence may not necessarily pose a high level of accident risk to the aircraft, severe and extreme turbulence due to mountain wave updraft and downdrafts, clear air turbulence and non-convective low-level wind shear (LLWS) may lead to structural failure and loss of control. As such, analysis of the level of turbulence expected during the course of a flight may aid in the determination of the safest route of flight.

Finally, convective potential is used to analyze the occurrence of severe weather along route through the use of specific thresholds (Chamberlain & Latorella, 2001). Convective weather such as thunderstorms creates a low level wind shear hazard during takeoff and landing and often produces severe or extreme convective turbulence aloft. Convective weather provides a difficult challenge for forecasters and its occurrence is often expressed in the form of probability. A relatively low potential for convective weather is indicated by a threshold which is below 15%, while a high potential for severe weather is indicated by a threshold which starts from above 15% up to about 30% or greater (Chamberlain & Latorella, 2001). Consequently, convective potential plays a significant role in the planning of flight routes based on the expected weather conditions. In addition to the potential strong winds, low ceilings and reduced visibility, these variables add to the foundation of the formulation of pilot personal weather minimums, and will thus played a major role in the development of survey questions which will be used for this research.

4.2 Characteristics of targeted users

This research involved the use of a questionnaire to issue specific survey questions to a population sample of GA light fixed-wing aircraft. Participants for this study were randomly selected from a previously acquired email list of ~7,000 GA pilots who fly light fixed-wing aircraft within the United States.

4.3 Data collection method

This research utilized quantitative research, which involved the use of a list of survey questions emailed to pilots. This survey method was specifically chosen for this research due to the advantages it offered such as inexpensiveness, practicality (allow for the extensive formulation of questions to fit the research category), non-time consuming (questionnaires can be issued to a large number of participants at the same time), scalability (easy to gather information from a large number of participants spread over a large geographical area), comparability (questionnaire data will be used to define the requirements of a software application) and easy visualization and analysis of data (Lefever, Dal & Matthiasdottir, 2007).

To further facilitate the analysis of data and grouping of participant responses according to the weather hazard importance, a four-point Likert scale was used for each of the responses. This scale was as follows –

(1) Not important
(2) Somewhat important
(3) Important
(4) Very important

The survey questions were formulated through the consideration of a combination of identified hazardous weather variables for en route or cruise operations as well as those specific for the departure and destination airports. As such, the 15 questions used for this research including –

1. How important is having daylight to make a flight?
2. How important is mountainous terrain when considering a flight?
3. How important is departing out of or landing at an airport in mountainous terrain?
4. How important is the availability of weather reporting at the destination or departure airport?
5. How important is having a weather forecast for surface visibility at the destination airport?
6. How important is having a weather forecast for surface visibility at the departure airport?
7. How important is having a weather forecast for ceiling at the destination airport?
8. How important is having a weather forecast for ceiling at the departure airport?
9. How important is having a forecast for ceiling along the route of flight?
10. How important is having a forecast surface visibility along the route of flight?
11. How important is having a weather forecast for wind speed and direction at the destination airport?
12. How important is having a weather forecast for wind speed and direction at the departure airport?
13. How important is determining the likelihood of turbulence along the route of flight?
14. How important is determining the likelihood of airframe icing along the route of flight?
15. How important is determining the forecast height of the lowest freezing level along the route of flight?

In addition to the questions above, the survey captured a few demographic elements for those pilots who responded as well as other targeted short answer questions to capture their risk tolerance. These questions required short responses from the participants that included:

1. Are you instrument rated? Yes or No response?
2. Do you regularly fly an aircraft with a certified ice protection system (IPS)? Yes or No response?
3. How many years have you been a pilot?
4. How many total flight hours have you logged?
5. What pilot certificate do you currently hold (student, private, commercial, ATP)?
6. If forecast, what intensity of airframe icing is considered too risky (e.g., trace, light, moderate, heavy)?
7. If forecast, what intensity of turbulence is considered too risky (e.g., light, moderate, severe, extreme)?

8. What is the average duration of your flights?
9. What is the maximum crosswind component you feel comfortable landing at an airport with sufficient runway width?
10. What is the maximum crosswind component you feel comfortable taking off at an airport with sufficient runway width?

4.4 Administration method

As stated earlier, a list of email addresses were previously acquired and emails were distributed to ~7,000 GA light fixed-wing aircraft pilots. Survey questions were administered via the Survey Monkey which is a popular survey application used to not only create, but also run professional surveys using an online platform. In general terms, the goal of this survey was to obtain a better comprehension of the importance of personal weather minimums and identify the sensible weather elements which are considered to be crucial to pilots when minimizing their exposure to hazardous weather. The survey also assisted in the definition of defaults and general settings that are applicable for most GA pilots. During the survey there were ~800 emails that were not deliverable. A total of 1,123 responses were received prior to the survey end time and compiled for this research.

4.5 Ethical considerations

Before the issuance of these questionnaires and after the successful selection of the population sample, participants were informed of the voluntary nature of this research, were given an opportunity to revoke their participation. In addition, the participants were assured of their anonymity and the safety of the information they provide through their responses. This information will only be used for this particular research and as such, will not be used to conduct research in other studies. Finally, participant responses were stored in a password-protected file within the computer used for this research, in order to further ensure the protection of participant information. A backup of the results of the survey was backed up on a secure Dropbox account.

It is common before conducting a survey such as this to get an approval through the Institutional Review Board (IRB). The survey to be conducted, however, meets the Exempt category under 45 CFR 46.104(d). Therefore, an IRB request was filed (IRB request number 188500) to apply for a waiver[6]. On November 19, 2020, the Office of Research Compliance at University of North Carolina at Charlotte (UNCC) granted a waiver as stated below, in part, in a letter received from the UNCC IRB (see Appendix A for the complete letter).

> "This submission has been reviewed by the Office of Research Protections and Integrity (ORPI) and was determined to meet the Exempt category cited above under 45 CFR 46.104(d). This determination has no expiration or end date and is not subject to an annual continuing review."

Furthermore, the original list of questions was modified to remove questions to reduce the overall workload required by the participants, and thus, shorten the time for participants to complete the survey. On January 22, 2021, the modification submission was approved by the ORPI.

4.6 Evaluation and rationale

After the completion of the survey process, participant responses were compiled and categorized according to importance of weather-related flight hazards. This categorization was used to create a better comprehension of the importance of personal minimums for GA light fixed-wing aircraft pilots within the United States. Relative importance of each of the weather variables under investigation (e.g., ceiling height, surface visibility, surface wind, airframe icing

[6] See https://research.uncc.edu/sites/research.uncc.edu/files/media/files/ExemptCategoriesGuidance.pdf

potential, turbulence potential and convective potential) was determined by use of the four-point Likert scale which was outlined earlier.

4.7 Software Application design, function, and components

The proposed software application was developed, in part, based on the results of the survey that were compiled and categorized. Some of the major functions implemented within the proposed application include: (1) personal minimum threshold storage and acceptance according to pilot specifications, (2) evaluation of route-based weather reports and forecasts in order to analyze the flight risk over possible departure times based on personal weather minimums and (3) the comprehensive display of results for the pilot after the route has been evaluated. Consequently, through the performance of these functions, this application enables accurate risk assessment based on personal minimum thresholds set by each pilot. More specifically, in order to perform its basic functions, the application provides weather reports and forecasts which are site-specific. Some of the sensible weather elements analyzed by the application include: surface visibility, surface wind speed and direction, ceiling height, sky coverage, turbulence aloft, airframe icing aloft and convective potential. Based on the literature review and the results of the survey, these define the critical elements which are needed by pilots to minimize their exposure to adverse weather based.

The application consists of seven primary capabilities: (1) collect and store various online weather reports and forecasts from the NWS and other aeronautical data from the FAA required by the application for route-based planning; (2) collect and store data from the user for aircraft-specific settings; (3) collect and store data from the user for personal weather minimum settings; (4) allow user to define, edit and store a route of flight; (5) evaluate personal weather minimums against forecast weather data along user-defined route for future departure times; (6) display the results from the risk assessment in an intuitive manner; and (7) organize and display to the user weather reports and forecasts to increase situational awareness along the proposed route of flight.

4.7.1 Aeronautical information database

Aeronautical data is provided by the FAA's National Airspace System Resource (NASR) system. This is the means for maintaining and storing a georeferenced database that documents the National Airspace System's (NAS) navigation infrastructure and the operational status of all of its various components. This provides to the application, in part, various navigation data (e.g., waypoints) used by pilots to define a route in the United States to include airports, seaports, heliports, navigation aids (NAVAID), intersections, fixes and other waypoints. This data is updated by the FAA on a 28-day cycle from a subscription that can be found here: https://www.faa.gov/air_traffic/flight_info/aeronav/aero_data/NASR_Subscription/. The application will import the necessary waypoints from the NASR database into the application's database every 28 days.

4.7.2 Aircraft-specific settings

In this application it is necessary to provide the capability for the pilot to enter the parameters or settings of the aircraft being used to fly the route. Aircraft fly at different altitudes and airspeeds and have different capabilities that must be considered by this application. This includes the aircraft's true airspeed at cruise altitude as well as rate of climb and descent and true airspeed (TAS) in the climb and descent. This is to facilitate the calculation of the aircraft's speed over the ground (ground speed) along the entire route. The calculation of the aircraft's ground speed determines the estimated time of arrival at intermediate waypoints and at the destination airport. Lastly, the aircraft weight class will be captured to determine the effect of turbulence intensity which is a direct function of the aircraft's weight. Defaults for these settings have been identified based on the survey results to create a starting point for the pilot. Entries for each aircraft setting will be stored in the application database on a per user basis.

4.7.3 Personal weather minimum category settings

Based on the results and analysis of the survey, specific personal weather minimum categories have been defined. Each category is bounded by an upper and lower limit. In some cases these limits will be obvious. For example, the lower limit of surface visibility will always be 0. Other limits have been chosen to fit within the overall responses of the survey or by the application of other rules or methods evaluated in this research. Also, the granularity of the scale and its definition has been captured for each personal weather minimum category.

The pilot uses the application to set or enter each personal weather minimum based on their own level of personal risk. This is captured through the use of a traffic light concept. That is, each personal weather minimum category has two values that need to be defined by the pilot that represents (1) the limit where the risk is deemed to be very high or unacceptable (red) and (2) the limit where the risk is deemed to be very low or acceptable (green). The former is referred to as the pilot's personal minimums for that category. The region between the acceptable and unacceptable risk will be deemed as cautionary (yellow) implying moderate risk. Defaults for these settings have been identified to create a starting point for the pilot. Entries for each personal weather minimum category are stored in the application database on a per user basis.

4.7.4 Route of flight entry

The primary capability for this application is to evaluate the weather along a pilot's proposed route of flight. A complete route consists of a departure and destination airport (or seaport or heliport) and optional route of flight consisting of one or more flyover waypoints. If no flyover waypoints are entered, the route will be considered a "direct" flight. As a result, the application provides a rudimentary route editor to enter the departure airport, destination airport and intermediate flyover waypoints defining the proposed route. Only airports and waypoints in the NASR database are allowed. Additionally, it is necessary for the pilot to enter the planned cruise altitude so that airframe icing and turbulence potential can be evaluated along the proposed route of flight. To control the complexity of the application, only a single altitude is allowed. Therefore, the route editor will have the capability for the pilot to set a single cruise altitude for the flight. The route and cruise altitude will be stored in the application database on a per user basis. A default route is not needed.

4.7.5 Weather reports and forecast data definition and collection

The primary goal of this research is to develop an application that can closely approximate the forecast weather along a proposed route of flight over a two to three day period enabling pilots to minimize their exposure to adverse weather. Pilots flying under VFR tend to inadvertently encounter IMC more often during the cruise phase of flight than at departure or destination airports (Lanicci, 2012). This is likely because they tend to emphasize the ceiling and visibility guidance only for the departure and approach phase of flight, but not during cruise (Blickensderfer, et al., 2017). When looking at the entire route, however, official forecast guidance issued by the NWS as terminal aerodrome forecasts (TAFs) are available at a very limited number[7] of airports. This generates two requirements that include (1) a forecast for adverse weather significant to aviation at thousands of additional airports throughout the United States; and (2) high resolution forecasts for adverse weather (e.g., clouds and reduced visibility) along the route of flight. In the past the NWS issued transcribed weather broadcasts (TWEBs) that provided route-based weather guidance for a 50-nautical mile wide corridor between selected terminal areas, but these have since been discontinued. Therefore, neither the NWS nor FAA provides such a route-based forecast for adverse weather.

Creating a route-based forecast is accomplished through online access to various datasets published by the NWS. These datasets are freely available and contain high spatiotemporal resolution digital forecasts that are routinely updated to maintain timely projections. It is not the intention of this research to determine the “best performing” forecasts for the application. Instead the goal is to collect data from various NWS sources that will allow the application to perform a complete and consistent evaluation of the weather along the proposed route of flight owing to the pilot’s personal weather minimum categories. Moreover, the data gathered will be limited, in general, to the region (Figure 5) over the conterminous United States and coastal waters[8]. The application is an automated decision-making tool; therefore, datasets will need to be of a digital form and are updated frequently to reflect the latest weather forecasts available.

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[7] There are ~700 airports for which the NWS issues Terminal Aerodrome Forecasts (TAFs).
[8] This includes southern Canada and northern Mexico and is the domain covered by the National Blend of Models gridded forecast for the conterminous United States.

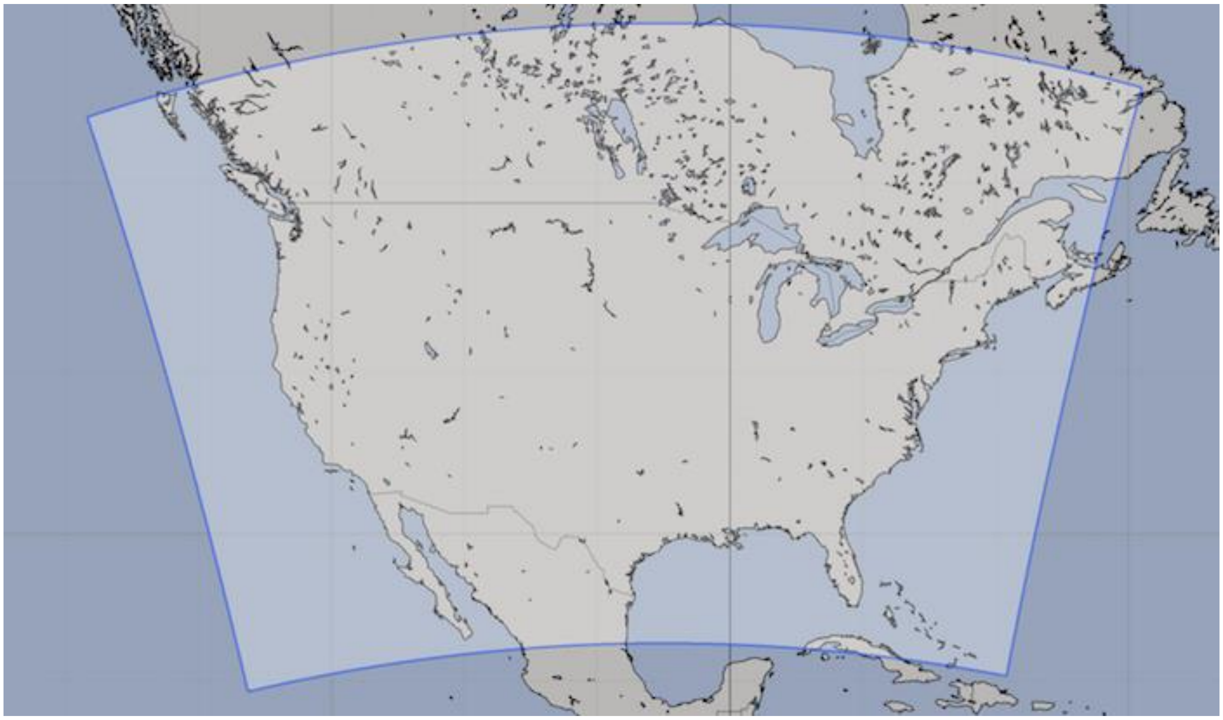

Figure 5. Forecast domain for the application that covers the conterminous United States, southern Canada and northern Mexico.

While GA pilots can plan cross-country flights that are less than one hour in duration, this application is designed to provide guidance for flight planning that has a minimum duration of one hour. Consequently, the time of departure provided in the application is set to an interval of one hour. The top of the hour is used as the reference point since many of the datasets ingested by the application are also valid at the top of the hour. It is assumed that a particular weather forecast persists from the top of the hour to the top of the next hour. For example, a dataset that is valid at 1200 UTC will be considered valid from 1200 UTC through 1259 UTC. This is also consistent with official advisories and forecasts (e.g., TAF) from the NWS that also assumes the forecast will persist from hour to hour (NWS, 2016).

Four primary forecast datasets were chosen as the foundation for the application's core weather data. All of these datasets are provided freely by the NWS and originate in a highly compact GRIdded Binary (GRIB) version 2 (GRIBv2) format and completely cover the entire forecast domain. These datasets are unpacked and stored in a geoJSON[9] format using a commercial-off-the-shelf MongoDB™ non-relational database. The datasets include the Global Forecast System (GFS), National Blend of Models (NBM), Forecast Icing Product (FIP), and Graphical Turbulence Guidance (GTG) product. Most GA aircraft are only certified to fly below 25,000 feet MSL. However, some pressurized single-engine and light twin-engine turbofan aircraft are certified to fly up to and including 45,000 feet MSL. Therefore, datasets utilized in this research will encompass a vertical resolution up to and including 45,000 feet MSL where applicable[10].

4.7.5.1 Global Forecast System (GFS)

The Global Forecast System (GFS) is a deterministic spectral model that provides an analysis and forecast with a lead time to 16 days (384 hours). The GFS is executed operationally by the National Centers for Environmental Prediction (NCEP) Central Operations (NCO) four times a day. GFS output is posted to a resolution of 0.25° equally spaced grid with an hourly temporal resolution to 120 hours, then 3-hourly for days 5-16.[11] However, this application will only provide forecast guidance to pilots over a period of 2-3 days.

The GFS dataset is retrieved using a GRIB filter capability from NOAA Operational Model Archive and Distribution System (NOMADS)[12]. This provides a subset of fields and pressure levels to allow for more efficient processing given the limited forecast data needed for the application. The GRIB filter allows the script to download only the fields for pressure levels of interest. The GFS model has 46 vertical standard pressure levels. To provide a reasonable

[9] GeoJSON is an open standard format specifically designed to represent the location of geographical features, along with their non-spatial attributes.
[10] The Forecast Icing Product (FIP) does not provide guidance above 30,000 feet.
[11] The application will only be considering forecasts with a lead time not to exceed 72 hours.
[12] See https://nomads.ncep.noaa.gov/

vertical resolution within the application, the levels included in the GRIB filter include 150 mb, 200 mb, 250 mb, 300 mb, 350 mb 400 mb, 450 mb, 500 mb, 550 mb, 600 mb, 650 mb, 700 mb, 750 mb, 800 mb, 850 mb, 900 mb, 925 mb, 950 mb, 975 mb, 1000 mb and the height of the 0°C isotherm (melting level).

Fields of interest from the GFS GRIBv2 dataset include –

(a) Relative humidity;
(b) ***u*** and ***v*** wind components;
(c) Freezing level height;
(d) Temperature; and
(e) Geopotential height of the pressure surface.

EVENT	Average Start Time	Average End Time
DATA DUMP AND PREP	08:47:05	08:53:46
ANALYSIS	08:53:58	09:21:42
T1534 FORECAST F000-F384	09:21:43	11:03:06
12hr PRODUCTS	09:27:57	09:32:52
24hr PRODUCTS	09:34:11	09:36:18
36hr PRODUCTS	09:37:40	09:39:46
48hr PRODUCTS	09:40:07	09:42:15
60-72hr PRODUCTS	09:43:40	09:49:04
84-120hr PRODUCTS	09:50:31	10:02:52
GFS MOS FORECAST	10:04:57	10:05:27

Figure 6. Average start and end time (UTC) of the 0600 UTC Global Forecast System (GFS) cycle.

It is not possible to predict the exact time the GFS dataset becomes available on NOMADS given that this may change from one execution cycle to the next. For example, the average start and end time (Figure 6) of the 0600 UTC cycle for the GFS model. On average, the GFS completes the 72 hour forecast products at ~0950 UTC. Under most circumstances, the 0600 UTC dataset is available for download on NOMADS shortly after 1000 UTC. Consequently, this temporal lag means the GFS analysis and hourly forecasts through four hours will be valid in the past and effectively rendering those hours unnecessary for this research. Therefore, hours 5, 6, 7, 8…72 will be downloaded and processed accordingly.

4.7.5.2 Airport forecasts using the National Blend of Models (NBM)

The National Blend of Models (NBM) is the newest high-resolution, statistically post-processed, multi-model guidance system provided by the NWS (Hamill et al., 2017). The NBM system utilizes an ensemble-based technique, which revolves around the combination of a consensus of forecasts derived from multiple similar model simulations (ensemble models) and multiple different deterministic model simulations. This provides a higher level of long-term accuracy, as compared to forecasts that rely on data which is derived from individual models (Gilbert et al., 2015). For instance, a simple average of the output of two or more statistical forecast models has been discovered to produce results which have higher levels of accuracy than those which consist of only individual model forecasts (Vislocky and Fritsch, 1997).

Essentially, NBM is considered to not only be a product, but also an approach which facilitates the extraction of weather guidance which is highly consistent from multiple forecast models. In this case, ensemble models are also included in the determination of NBM forecasts. As such, NBM can be considered to be a meta-ensemble (combination of ensembles) given its advanced utilization of a blend of both non-ensemble and ensemble models. A chosen forecast model set, which includes ensembles, therefore becomes the source from which the NBM combines various forecasts to yield more accurate results. The blending of this multi-model-based guidance then occurs through the use of a 2.5 km National Digital Forecast Database (NDFD) grid statistically compressed bias-correction system, thus creating a higher level of accuracy for forecast results (Veenhuis, 2015).

During its hourly initialization, the NBM facilitates the production of a number of gridded datasets that contain a variety of elements critical to the U.S. aviation sector. Unlike the forecasts from the GFS Model Output Statistics (MOS) and Localized Aviation MOS Program (LAMP) that provide a categorical forecast for ceiling height and surface visibility, the NBM ensures the continuous automated provision of visibility and ceiling forecasts for selected airports throughout the United States, Canada and Mexico (Glahn et al., 2017). Moreover, the NBM also includes the lowest cloud base (LCB) for scattered (SCT) cloud layers or for cloud layers which consist of only a few (FEW) clouds below the forecast ceiling height or when an unlimited ceiling is forecast.

On September 29, 2020, NBM version 4.0 (NBMv4.0) moved into an operational status. There were many distinct improvements from NBM version 3.2 (NBMv3.2) that have yet to be considered for this research but show significant promise. According to Adam Schnapp who is the aviation/retrospective lead of the NWS Meteorological Development Laboratory (MDL), ceiling and visibility with NBMv4.0 uses the LAMP for the near-term (1-36 h lead time) with two key differences:

(1) The NBM cycle is the LAMP model from the previous cycle, so the disseminated LAMP products will catch onto observation changes first.

(2) The NBM post-processes ceiling height so that it is consistent with the sky cover forecast. The result is that sometimes the ceiling height that comes from LAMP is removed when the NBM sky cover forecast is less than 57% (Schnapp, 2020).

Consequently, the integration of the NBMv4.0 into the application for this research will enable the provision of weather guidance significant to aviation for ~9,000 stations[13], including

[13] Full National Blend of Models station list can be found here: https://vlab.ncep.noaa.gov/web/mdl/nbm-stations-v4.0.

most of the conterminous public-use airports[14] in the United States (NWS, 2020). The NBM data is provided by the NWS in two forms; the first (Figure 7 and Figure 8) is an alphanumeric message (tabular bulletin) for an airport and the second is a high resolution gridded form to be discussed later. Fields of interest in the NBMv4.0 tabular bulletin includes –

(a) Ceiling height (CIG);
(b) Sky cover (SKY);
(c) Lowest cloud base (LCB);
(d) Surface visibility (VIS);
(e) Wind speed (WSP), wind gust (GST) and wind direction (WDR);
(f) Surface temperature (TMP)
(g) Surface dewpoint temperature (DPT)
(h) 1 h thunderstorm probability (T01) and 3 h thunderstorm probability (T03);
(i) 1 h probability of precipitation (P01) and 6 h probability of precipitation (P06);
(j) Probability of snow (PSN);
(k) Probability of freezing rain (PZR);
(l) Probability of rain (PRA); and
(m) Probability of ice pellets (PPL).

The tabular bulletin for each NBM station (airport) is generated for every NBMv4.0 forecast cycle and the result is published on the NOMADS site. These are processed every hour at prescribed times. The NWS creates these tabular bulletins by post-processing the NBMv4.0 high resolution gridded data. Jeffrey Craven, branch chief of the NWS Meteorological Development Laboratory's Statistical Modeling Division explained the process of how these tabular bulletins are generated from the high resolution NBMv4.0 gridded forecast.

> "The stations take the nearest grid point, and then for temperature they make a correction for the difference in elevation between the gridded terrain value and the actual station elevation value."

As given in Table 2, NBMv4.0 generates five tabular bulletins[15]. In this research there are two specific NBMv4.0 bulletins that are utilized, namely, NBH (hourly) and NBS (short range). The NBH bulletin (Figure 7) provides forecast guidance for hourly projections of 1 to 25 hours.

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[14] This equates to ~3,500 public-use airports.
[15] See https://www.weather.gov/mdl/nbm_text

The NBS bulletin (Figure 8) provides short-range guidance for projections with a 3 h time step to 72 hours[16]. Each row in the bulletin represents a different predicted weather element with each column designating a specific forecast projection (in UTC). The first column in each tabular bulletin depicts the predicted element's abbreviation. For example, the row beginning with DPT represents the NBMv4.0 forecast for surface dewpoint temperature.

Table 2. There are five NBM alphanumeric messages available that cover different elements and time scales. Actual forecast hours will change according to the NBM cycle time. *Forecast hours listed in the table below are for the 0000 UTC and 1200 UTC model cycles. Table was constructed from https://vlab.ncep.noaa.gov/web/mdl/nbm-textcard-v4.0.

Product name	Product type	Time step	Forecast hours covered
NBH	Hourly	1 hour	1 - 25
NBS	Short (range)	3 hours	6 – 72*
NBE	Extended (range)	12 hours	24 – 192*
NBX	Super-extended (range)	12 hours	204 – 264*
NBP	Probabilistic (extended period)	12 hours	24 – 228*

The first line of the hourly (Figure 7) and short-range (Figure 8) tabular bulletins include the station identifier, tabular bulletin description, date of the forecast and forecast cycle. The next two lines list the valid times for each column relative to UTC. The lines following consist of various predicted weather elements (e.g., temperature). These elements vary by bulletin type, region and forecast cycle time in some cases. Any value shown as 998 or greater will be printed as 998. Any forecast element with a displayed value less than -98 is shown as -98. A value of -99 for any forecast element indicates missing data. In the event all columns of data are missing for a particular forecast element, the line for that element is excluded from the bulletin altogether. While not an often occurrence, this can happen when one or more members of the national blend miss the NBM data cutoff time.

[16] The forecast projections for the short-range bulletin are exclusively valid at the synoptic times of 0000, 0300, 0600, 0900, 1200, 1500, 1800 and 2100 UTC independent of the execution cycle time of the National Blend of Models (NBM). Depending on the specific NBM cycle time, however, the last projection in the short-range bulletin may represent a lead time of 70, 71 or 72 hours.

These two bulletins intentionally overlap for some of the early forecast projections. That is, they overlap for a subset of possible valid times. It is important to note that while many of the rows depict the same weather element (e.g., TMP) each bulletin has a few unique forecast fields not shared between them[17] (e.g., P01 and P06). Therefore, to provide a consistent forecast at the highest temporal resolution, the two bulletins are electronically merged to create a single bulletin consisting of the union of the two. The resulting bulletin is then parsed to draw out the fields of interest before being converted to geoJSON[18]. This is necessary so that each station will have a single NBMv4.0 document stored in the MongoDB for each airport and valid time[19]. For hourly projections beyond 25 hours, it is assumed that the latter forecast projections will persist for a three hour period. This is done to avoid having departure times that do not contain a complete set of forecast guidance.

[17] The unique rows in the two NBMv4.0 tabular bulletins correspond to probabilistic forecasts.
[18] The airport latitude/longitude is retrieved from the navigation database collection and appended to create a georeferenced JSON document.
[19] This is done to optimize the retrieval of the data at a later time.

```
KBUF    NBM V4.0 NBH GUIDANCE   12/26/2020  1300 UTC
UTC  14 15 16 17 18 19 20 21 22 23 00 01 02 03 04 05 06 07 08 09 10 11 12 13 14
TMP  25 25 26 26 26 27 28 27 27 27 27 27 27 27 27 26 26 26 26 26 25 25 26 26 27
TSD   2  2  2  2  2  2  1  1  1  1  1  1  1  1  1  1  1  2  2  2  2  2  2  2  2
DPT  18 18 18 18 18 19 19 19 19 19 18 19 19 19 19 19 19 19 18 19 19 19 19 20 20
DSD   2  2  2  2  2  2  1  1  1  1  1  1  1  1  1  1  1  1  1  1  2  2  2  2  2
SKY  93 97 98 93 91 92 82 87 76 48 49 62 55 58 53 60 48 48 34 53 50 60 61 76 83
SSD   4  3  3 13 12  3 15 18 29 29 39 38 37 37 38 39 38 38 36 40 37 31 32 21 11
WDR  24 24 24 24 24 25 25 25 25 25 26 26 26 26 26 26 25 25 25 25 24 23 22 21 20
WSP  16 15 15 16 16 15 15 15 14 13 12 11 12 10 10  9  9  8  7  6  6  7  6  6  7
WSD   2  2  3  2  2  2  2  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
GST  23 24 25 26 26 25 24 23 22 21 19 18 17 15 14 13 12 10 10 10 10 10  8  8 10
GSD   3  3  3  2  3  3  2  3  3  2  2  3  3  3  3  3  2  2  2  2  2  1  2  2  2
P01  15 22 37 46 45 36 19  8  3  1  0  0  1  0  0  0  0  1  1  0  2  2  8 13  7
P06                               33                 5                 2
Q01   1  1  3  6  4  2  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  1  0
T01   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
PZR   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0 12 30 36 40 48
PSN 100100100100100100100100100100100100100100100100100100100 88 70 65 60 52
PPL   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
PRA   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
S01   1  1  5 10  8  4  1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  1  0
SLV   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
I01   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0
CIG  11 22 13 13 15 22 22 18 27-88-88 27-88 27-88 27-88-88-88-88-88 27 22 22 22
MVC  56 54 88100 90 66 57 59 51 40 40 42 45 46 48 43 43 45 46 47 49 50 49 49 47
IFC  30 21 16 20 10  3  2 12  2  3  2  5  5  7  5  3  3  1  0  0  0  0  0  2  4
LIC   1  0  0  1  0  0  0  1  0  0  0  1  1  2  2  0  0  0  0  0  0  0  0  0  0
LCB  11 22 12 11 14 21 22 18 27 40 36 27 48 27 50 27 50 45 46 33 50 19 18 11 11
VIS   7 10  7  7  7 60 90 90100100100100100100100100100100100100100100100100100
MVV  62 43 61 74 62 29 26 22 22 17 18 16 15 16 16 15 14 10  9  8  8  6  8 10 12
IFV  55 38 51 65 53 20 19 16 15 11 13 10  9 10 10 11  8  4  2  3  1  1  4  5  5
LIV  33 22 27 37 29  9  9  9  5  4  4  3  2  3  3  2  1  0  0  1  0  0  1  1  2
MHT  21 25 25 25 27 25 24 20 17 15 11 11  9  8  9  7  7  6  6  6  6  6  6  6 10
TWD  26 24 24 24 24 26 26 26 26 26 26 26 27 27 27 27 26 26 26 27 27 27 23 23 19
TWS  23 23 21 25 24 21 21 22 21 21 16 17 17 16 16 14 13 13 12 12 12 11  6  6 10
HID                                3                 3                 3
SOL   6  9  8  9  9 11 14  7  2  2  1  0  0  0  0  0  0  0  0  0  0  0  0  1  4
```

Figure 7. Hourly alphanumeric message for Buffalo, N.Y. from the 1300 UTC run of the National Blend of Models (NBMv4.0) on December 26, 2020. Each row depicts a predicted forecast element, and each column is represents a single valid time.

```
KBUF    NBM V4.0 NBS GUIDANCE   12/26/2020  1300 UTC
DT /DEC  26/DEC  27                /DEC  28                /DEC  29
UTC  18 21 00 03 06 09 12 15 18 21 00 03 06 09 12 15 18 21 00 03 06 09 12
FHR  05 08 11 14 17 20 23 26 29 32 35 38 41 44 47 50 53 56 59 62 65 68 71
TXN                    23          40          34          41          23
XND                     2           2           2           2           1
TMP  26 27 27 27 26 26 26 28 33 35 35 37 40 40 41 38 37 35 32 29 27 26 25
TSD   2  1  1  1  1  2  2  2  1  2  2  2  3  2  2  1  1  1  2  2  2  2  2
DPT  18 19 18 19 19 19 19 21 22 23 24 26 28 31 33 32 29 26 23 19 17 15 15
DSD   2  1  1  1  1  1  2  2  1  2  2  2  3  2  2  1  1  1  2  2  2  2  2
SKY  91 87 49 58 48 53 61 80 65 76 72 89 89 87 89 94 91 84 76 78 70 69 62
SSD  12 18 39 37 38 40 32 27 29 18 24  8  7  7  5  4  4 10 15 12 17 14 17
WDR  24 25 26 26 25 25 22 20 19 14 17 18 18 20 21 24 25 26 27 27 27 28 28
WSP  16 15 12 10  9  6  6  7  8  8  9 12 15 16 16 17 17 16 14 13 14 12 11
WSD   2  1  1  1  1  1  1  2  1  1  2  3  2  3  2  2  2  2  3  3  2  2  2
GST  26 23 19 15 12 10  8 11 12  9 11 16 26 27 25 26 25 23 18 17 16 16 13
GSD   3  3  2  3  2  2  2  3  3  2  4  6  4  5  4  3  4  2  5  4  3  3  2
P06        33     5     2     1     2    10    69    41    22    19    16
P12                    10           3          70          60          34
Q06         1     0     0     0     0     0    10     2     0     0     0
Q12                     0           0          10           2           0
DUR                     1           1           3           1           0
T03   0  0  0  0  0  0  0  0  0  0  0  0  1  1  1  0  0  0  1  1  1  1  1
T06         1     1     0     0     0     1     1     1     2     2     3
T12                     1           0           1           3           5
PZR   0  0  0  0  0  0 36 50  0  0  1  0  0  0  0  0  0  0  0  0  0  0  0
PSN 100100100100100100 65 50100100 69  3  3  0  4  0 56100100100100100100
PPL   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
PRA   0  0  0  0  0  0  0  0  0  0 62100 97100 96100 58  0  0  0  0  0  0
S06         5     0     1     1     0     0     0     0     1     2     3
SLV   0  0  0  0  0  0  0  0  0  2 12 35 34 23 25 13  5  2  0  0  0  0  0
I06         0     0     0     1     0     0     0     0     0     0     0
CIG  15 18-88 27-88-88 22 27100-88110 70 48 14 13 12 21 22 23 37 38 40 21
IFC  10 12  2  7  3  0  0  4  1  0  3  0  0 27 19 12  3  3  3  0  0  0  0
LCB  14 18 36 27 50 33 18 25100160110 39 29 10  9 10 13 22 22 23 25 31 21
VIS   7 90100100100100100100100100100100 70 20 30100100100100100100100100
IFV  53 16 13 10  8  3  4  7  5  4  3  6 16 30 23 14 12 12  8 11  6 11  4
MHT  27 20 11  8  7  6  6 13 15  6  7  7  8  9  9 16 29 26 16 23 15 25 17
TWD  24 26 26 27 26 27 23 19 19 14 18 18 18 20 22 24 26 27 28 27 27 28 29
TWS  24 22 16 16 13 12  6 11 13  4 12 16 19 19 21 25 24 21 16 15 15 20 15
HID         3     3     3     4     4     4     3     3     3     3     3
SOL   9  7  1  0  0  0  0  9 32  9  2  0  0  0  0  2 12 16  9  0  0  0  0
```

Figure 8. Short-range alphanumeric message for Buffalo, N.Y. from the 1300 UTC run of the National Blend of Models (NBMv4.0) on December 26, 2020. Each row depicts a predicted forecast element and each column is represents a single valid time.

4.7.5.3 Gridded forecast using the National Blend of Models (NBM)

In addition to the alphanumeric messages that represent forecasts valid at a station (airport), the NBMv4.0 forecast guidance is also available from the NWS in a binary gridded form with a resolution of 2.5 km over the application's domain. This provides the capability to evaluate the critical adverse weather elements such as ceiling height, surface visibility and convective potential across the entire proposed route of flight. It also allows the application to build a relevant forecast for airports that are not included in the NBM tabular dataset[20] by utilizing the nearest grid point. An airport's terminal area is defined by the NWS as "the area within five (5) statute miles (SM) of the center of an airport's runway complex" (NWS, 2016). Therefore, with a native resolution of 2.5 km, a grid point will be highly representative of the airport's terminal area.

The gridded forecast is generated for every NBMv4.0 hourly forecast cycle and the result is published on the NOMADS site. These forecasts are processed every hour at prescribed times. Fields of interest in the NBMv4.0 gridded forecast are similar to the tabular bullet and includes –

(a) Ceiling height;
(b) Sky cover;
(c) Lowest cloud base;
(d) Surface visibility;
(e) Wind speed, wind gust and wind direction;
(f) Surface temperature;
(g) Surface dewpoint temperature;
(h) 1 h thunderstorm probability;
(i) 1 h probability of precipitation; and
(j) Predominant weather.

The gridded NBMv4.0 forecast is issued hourly with hourly forecast projections for 1 h to 36 h and thereafter at a three hour interval from 37 h to 72 h. Similar to the tabular bulletins for the short-range forecast, projections beyond 36 hours for the gridded forecast are exclusively

[20] These may include private airports or seaports.

valid at the synoptic times of 0000, 0300, 0600, 0900, 1200, 1500, 1800 and 2100 UTC independent of the execution cycle time of the NBM. This implies that forecast hours will change according to the NBM cycle time. However, for the sake of simplicity and to lessen the overall data processing needed, the NBMv4.0 gridded forecasts for the projections beyond 36 hours are processed every third run to include cycle times for 0200, 0500, 0800, 1100, 1400, 1700, 2000 and 2300 UTC. This produces a forecast for 38 to 71 hours with a temporal resolution of 3 hours[21]. Similar to the tabular bulletins, it is assumed that the forecast projections prior to 36 hours will persist for an hour and beyond the 36 h projection they will persist for a three hour period.

Table 3. Precipitation potential index values and associated precipitation type categories taken from (Huntemann, et al., 2012).

Precipitation Potential Index value	Probability code for precipitation types	Coverage category for convection/thunderstorms
0-14	None	None
15-24	Slight chance (SChc)	Isolated (Iso)
25-54	Chance (Chc)	Scattered (Sct)
55-74	Likely (Lkly)	Numerous (Num)
75-100	Definite (Def)	Definite (Def)

One of the more interesting fields forecast by NBMv4.0 is the predominant weather field. This is useful to determine the precipitation type expected at the surface (e.g., freezing rain) and also whether or not convective precipitation is expected. In short, NBMv4.0 first takes each conditional precipitation type probability and converts it to a "potential index" that is scaled to the 12 h probability of precipitation value (Huntemann, et al., 2012). It then gets multiplied by the precipitation potential index (PPI) to “unconditionalize” it (Huntemann, et al., 2012). These PPI values range from 0 to 100 and resemble the 12 h probability of precipitation values in terms

[21] This includes forecast projections of 38, 41, 44, 47, 50, 53, 56, 59, 62, 65, 68 and 71 h.

of magnitude (Huntemann, et al., 2012). Probability thresholds (Table 3) are then applied to categorical values. These categories are assigned for each precipitation type, so it is possible to have “Likely” chance of snow and “Slight chance” of freezing rain together. Table 4 provides some examples of typical predominant weather codes that can be generated by NBMv4.0.

Table 4. Examples of translations of predominant weather codes provided by the NBMv4.0 predominant weather field.

No significant weather	<NoCov>:<NoWx>:<NoInten>:<NoVis>:
Slight chance of showers and isolated thunderstorms	SChc:RW:-:<NoVis>:^Iso:T:<NoInten>:<NoVis>:
Chance of showers and scattered thunderstorms	Chc:RW:-:<NoVis>:^Sct:T:<NoInten>:<NoVis>:
Chance of snow and slight chance of freezing rain	Chc:S:-:<NoVis>:^SChc:ZR:-:<NoVis>:
Definite chance of snow and slight chance of freezing rain	Def:S:-:<NoVis>:^SChc:ZR:-:<NoVis>:

Among other uses in the application, the predominant weather field is primarily leveraged to determine the convective potential along the route of flight using categorical scale. From a pilot’s perspective, deep, moist convection should be avoided due to the likelihood of severe or extreme convective turbulence and the possibility of low-level convective wind shear. There are two categories to consider, namely, showers and thunderstorms. Thunderstorms imply the potential for lightning; however, not all dangerous deep, moist convection contains lightning. Consequently, showery precipitation is just as important to consider in determining the convective threat.

At this point in time, NBMv4.0 does not directly provide the PPI. Therefore, it must be inferred using the predominant weather field. For this research a 6-level categorical thunderstorm risk parameter called “convective potential” was devised to determine the risk of convection along the route of flight. The convective potential (Table 5) is determined by uniquely combining both the showery precipitation likelihood with the thunderstorm likelihood from the NBMv4.0 predominant weather field to produce a convective potential forecast.

Table 5. Predominant weather to convective potential forecast mapping.

Predominant weather field	Convective potential
Does not contain showers (RW) or Thunderstorms (T)	**None**
Contains SChc:RW and only Iso:T	**Very low**
Contains Chc:RW and (Iso:T or Sct:T)	**Low**
Contains Lkly:RW and Iso:T or Sct:T)	**Medium**
Contains Lkly:RW and (Def:T or Num:T)	**High**
Contains Def:RW and (Def:T or Num:T or Sct:T or Iso:T)	**Very high**

4.7.5.4 Forecast Icing Product (FIP)

Airframe icing occurs in clouds and freezing precipitation when the temperature is at or below 0°C and when supercooled liquid water is present. Airframe icing[22] presents a significant hazard to aviation and most GA aircraft do not possess a certification that permits flight into known icing conditions and must rely on forecast guidance to avoid areas containing supercooled liquid water (Rasmussen et al., 1992). This has led researchers in the past two decades to develop specialized icing forecast guidance post-processed from deterministic forecast models, a general technique referred to as “data mining” the results of NWP model output (Thompson et al, 2017). This includes two automated diagnostic tools called the Current Icing Product (CIP) and Forecast Icing Product (FIP).

Both of these tools provide an aircraft-independent integrated icing diagnostic algorithm designed to depict the threat of in-flight airframe icing over the contiguous United States and southern Canada (Lee, et al., 2007). While CIP provides an hourly analysis of airframe icing valid at the top of the most recent hour, FIP is a forecast of those conditions and is more relevant

[22] Induction icing also represents a significant hazard to aviation, but the scope of this research is focused entirely on airframe icing.

for the application of this research. The output depicts the icing threat interpolated to 1000-ft altitude levels that extend from the surface to 30,000 feet MSL[23].

For the evaluation of airframe icing aloft along the route of flight, the Forecast Icing Product (FIP) will have a greater overall impact. Given that FIP is a forecast, it has to depend on the RAP model to emulate all of the observations that CIP normally has at its disposal. For example, cloud cover determination for CIP primarily comes from satellite and surface observations. In FIP, model forecasts of relative humidity and other model parameters are used to derive the locations of clouds, their cloud base heights, cloud top heights and cloud top temperature (Mcdonough, et al., 2004).

The FIP algorithm uses fuzzy logic and interest maps of the main meteorological contributors to airframe icing to determine the icing environment for the forecast domain (Figure 5) covering the conterminous United States, southern Canada and northern Mexico. These membership functions have been developed for the RAP model forecast and derived fields and are combined to produce three forecast outputs governed using a decision tree (Wolff, et al., 2009). The surface precipitation type is determined (Figure 9) along with cloud cover (e.g., scattered, broken, overcast) and various cloud attributes. Surface precipitation type is used to control which model inputs are combined and how they are ultimately weighted in the FIP algorithm.

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[23] Due to very cold temperatures, airframe icing is rare outside of deep, moist convection at an altitude above FL300 or 30,000 feet MSL.

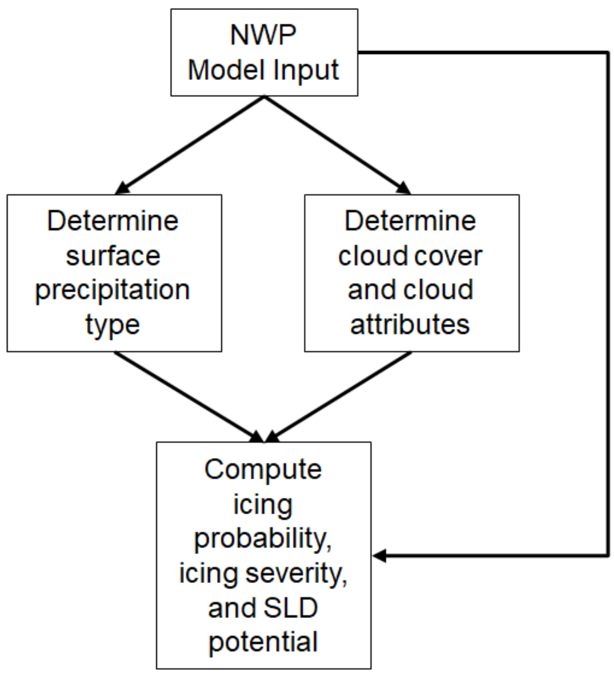

Figure 9. The Forecast Icing Product (FIP) algorithm for determining icing probability, icing severity and supercooled large drop (SLD) potential based on cloud cover attributes and precipitation type.

The algorithm for FIP pulls several NWP model fields to include temperature (and potential temperature), vertical velocity, relative humidity, condensate (ice and liquid), convective available potential energy, convective inhibition and quantitative precipitation forecast (Wolff, et al., 2009). Model forecast for temperature and relative humidity provide some of the largest contributions for determining the icing environment. To determine the cloud top, earlier versions of the FIP cloud scheme searched down from each column in the model for a relative humidity value greater than 70% (Mcdonough, et al., 2004). In this scheme the cloud top height was set to one model level higher, and this was later determined to be inefficient and lowered icing probability values due to colder (higher) cloud top temperatures (Wolff, et al., 2009). Therefore, the latest version of FIP uses other model fields in addition to model relative humidity such as potential temperature, total condensate and vertical velocity within a weighting function to determine the cloud top height (Wolff, et al., 2009). The new algorithm now determines the cloud top height by looking for regions in the column where the total condensate and relative humidity gradients show a transition from cloudy (moist) to clear air (Wolff, et al., 2009). Moreover, potential temperature in the column is also used to locate the altitude where potential temperature begins to increase with height which is a way to mark the transition altitude where the air is rapidly drying out implying the altitude of the cloud top (Wolff, et al., 2009). This ultimately gives a more accurate determination of the cloud top temperature leading to a more realistic forecast of icing probability.

The cloud base in FIP is determined by searching up from the lowest model layer near the surface for a relative humidity greater than 80% (Mcdonough, et al., 2004). However, it is common to see the model boundary layer have a relative humidity above 80%, even in cloud-free air (Mcdonough, et al., 2004). This means that FIP can sometimes “detect” clouds in places where they did not actually end up occurring. Consequently, it might forecast icing in cloud-free areas at times, while CIP will never indicate icing in a place where it did not first diagnose clouds or precipitation. To determine multiple cloud layers, the FIP algorithm first identifies a minimum of three consecutive hybrid levels where the humidity is less than 50%, with surrounding layers below and above that evaluate to a humidity greater than 70%; this increases the chances that the dry layer in between is more likely to prevent precipitation originating from the upper cloud to evaporate/sublimate before falling into the lower cloud layer (Mcdonough, et al., 2004).

Having an accurate forecast for airframe icing requires a scenario-based approach especially to determine the icing severity. At the core of this is the determination of precipitation and precipitation type (e.g., freezing rain). Studies have shown that freezing rain events not only produces supercooled large drop (SLD) icing aloft, but also increases ground icing events which is dangerous for all aircraft types (Bernstein, et al., 2000).

The original FIP algorithm for forecasting precipitation used a quantitative precipitation forecast (QPF) threshold of 0.2 mm over a three-hour period to signal a precipitation event (Mcdonough, et al., 2004). It was found later that using QPF in this way over-forecasts precipitation and does not pinpoint when precipitation is actually occurring given the resulting forecast is valid at a specific time, not over a period of time (Wolff et al., 2009).

This was subsequently changed to use condensate forecasts (e.g., rain, cloud ice, snow, cloud water, and graupel) from the model to determine where and when precipitation is expected to occur in the atmosphere (Wolff et al., 2009). To determine if a particular grid point is experiencing precipitation, the newest FIP algorithm looks at the lowest three model layers near the surface to determine if the maximum precipitable condensate above the terrain is more than 0.01 g kg^{-1} (Wolff et al., 2009). Convection is not represented well in the RAP given that it is parameterized; therefore, the FIP uses a separate algorithm for forecasting convection (Adriaansen et al., 2020). Moreover, precipitation type is identified to determine if rain, drizzle, snow, freezing rain, freezing rain and ice pellets are expected. The precipitation and type can be used in the scenario-based approach increase or decrease the icing severity and also determine if icing may be present below the cloud base due to falling freezing precipitation (e.g., freezing rain, freezing drizzle or ice pellets) (Mcdonough, et al., 2004).

Each hour FIP produces 3D grids to include –

(1) Calibrated icing probability forecast;

(2) Categorical icing severity forecast; and

(3) Supercooled large drop (SLD) icing potential.

It is worth noting that the SLD analysis and forecast for FIP is an uncalibrated potential field and does not represent true probabilities (Wolff, et al., 2009). A higher potential simply implies there is a greater likelihood SLD is present.

Table 6. Icing intensity values and their definitions in the pilot reporting system as defined in the Aeronautical Information Manual (FAA, 2020).

Intensity	Aircraft reaction
Trace	"Ice becomes noticeable. The rate of accumulation is slightly greater than the rate of sublimation. A representative accretion rate for reference purposes is less than ¼ inch per hour on the outer wing. The pilot should consider exiting the icing conditions before they become worse."
Light	"The rate of ice accumulation requires occasional cycling of manual deicing systems to minimize ice accretions on the airframe. A representative accretion rate for reference purposes is ¼ inch to 1 inch per hour on the unprotected part of the outer wing. The pilot should consider exiting the icing condition."
Moderate	"The rate of ice accumulation requires frequent cycling of manual deicing systems to minimize ice accretions on the airframe. A representative accretion rate for reference purposes is 1 to 3 inches per hour on the unprotected part of the outer wing. The pilot should consider exiting the icing condition as soon as possible."
Severe	"The rate of ice accumulation is such that ice protection systems fail to remove the accumulation of ice and ice accumulates in locations not normally prone to icing, such as areas aft of protected surfaces and any other areas identified by the manufacturer. A representative accretion rate for reference purposes is more than 3 inches per hour on the unprotected part of the outer wing. By regulation, immediate exit is required."

The reporting of icing intensity through a pilot weather report (PIREP) is somewhat subjective and often depends on the pilot's own previous experiences and perception of the event. Nevertheless, pilots are given specific guidelines by the FAA (Table 6) on how to report airframe icing using four major categories to include (1) Trace; (2) Light (2) Moderate; and (4) Severe. Note that pilots may also report intermediate categories for airframe icing intensity such as "light to moderate" as a way to bridge between two major categories.

Table 7. GRIBv2 code table for icing as documented in Table 4.207 by the World Meteorological Organization (WMO).

Code figure	Categorical meaning
0	None
1	Light
2	Moderate
3	Severe (unused)
4	Trace
5	Heavy

The categorical icing severity forecast for FIP is encoded in the binary GRIBv2 dataset (Table 7) as defined by the World Meteorological Organization (WMO). There are two oddities for this field worth mentioning. From lowest to highest, the FAA defines severity (Table 6) in the Aeronautical Information Manual (AIM) as trace, light, moderate and severe and is based on the rate of ice accumulation on aircraft surfaces (FAA, 2020). When CIP and FIP were first introduced, the WMO already had a mapping of icing severity for none, light, moderate and severe and did not have a categorical value reserved for Trace. As a result, Trace was mapped to a value of 4. Moreover, the FIP algorithm does not utilize the “Severe” category. Advisory Circular 91-74B from the FAA defines the term “severe icing” as being aircraft dependent and represents how the aircraft reacts to the meteorological conditions (FAA, 2015). FIP is designed to be an aircraft-independent analysis and forecast. Consequently, the category of “Heavy” is used to represent worst meteorological severity and was mapped to a value of 5. FIP is described in FAA Advisory Circular 00-45H, Change 2 as supplementary guidance for pilots to determine the potential of known icing conditions (FAA, 2016). This makes FIP optimal given that many pilots are currently familiar with this forecast guidance.

The FIP dataset becomes available on NOMADS every hour at prescribed times and arrives on NOMADS in a collection of several GRIBv2 files at flight levels from 1,000 to 30,000 feet MSL (in increments of 1000 feet) that are downloaded and processed over a period of ~20 minutes. These are downloaded and converted to geoJSON format at a 13 km resolution to replace the previous FIP dataset in the MongoDB. The FIP guidance provides a 1 h, 2 h, 3 h, 6 h, 9 h, 12 h, 15 h and 18 h lead time with each hourly execution. Similar to other guidance used in this research, the top of the hour is used as the valid reference time for these icing forecasts. It is assumed that the weather forecast persists from the valid time at the top of the hour to the valid time for the next available forecast hour.

4.7.5.5 Graphical Turbulence Guidance (GTG) product

While there are some restrictions to flying a GA aircraft into known or forecast icing conditions, flying into regions where dangerous turbulence exists is not specifically regulated owing to the fact that turbulence is largely a "microscale" phenomenon and extremely difficult to predict with any certainty. However, encounters with moderate or greater turbulence aloft have caused serious injuries and fatal accidents to the pilot and/or passengers flying fixed-wing light aircraft and helicopters (Sharman, et al., 2006). In the past two decades, this has led researchers to develop a completely automated turbulence forecasting system called the Graphical Turbulence Guidance (GTG) product.

For the evaluation of turbulence aloft along the route of flight, the automated GTG product is used to provide a forecast for turbulence covering the application's domain. The GTG algorithm blends NWP model-based turbulence diagnostics from the 13 km RAP model with available turbulence observations using a weighted sum computed to align with recent PIREPs (Klimenko et al., 2011). The weighted ensemble mean of diagnostics is calculated as

$$\text{GTG}\ (\mathbf{EDR}) = W_1D_1 + W_2D_2 + W_3D_3 + \ldots$$

where D is from NWP model output fields (e.g., winds, temperature) and W is the associated weight (Sharman et al., 2006).

The result is a 13 km resolution 3D gridded forecast for clear air turbulence (CAT) and mountain wave turbulence (MWT) at flight levels from the surface to 45,000 feet MSL (in increments of 1000 feet) and mapped to a common aircraft independent turbulence intensity scale called eddy dissipation rate (EDR). The values of EDR range from 0 to 1.0 m^2/s^3 where 0 is “smooth” and a value of 1 is indicative of extreme turbulence for most aircraft types.

When the EDR is large, the atmosphere is dissipating its energy quickly and turbulence intensity is generally high in that region. But the implication for aircraft bumpiness (what it feels like in the cockpit) ultimately depends on the weight class of the aircraft. That is, a Boeing 787 jumbo jet will experience turbulent mixing differently than a light fixed-wing aircraft such as a Cessna 172. For example, an EDR value of 0.2 m^2/s^3 may create moderate turbulence for a Cessna 172 and light turbulence for a Boeing 787. In the end, pilots need to be able to map what values of EDR equate to specific intensity of turbulence to determine the overall flight risk depending on the type of aircraft they are flying.

The reporting of turbulence intensity through a PIREP is very subjective and often depends on the pilot’s own previous experiences and perception of the event. Nevertheless, pilots are given specific guidelines by the FAA (Table 8) on how to report turbulence using four major categories to include (1) Light; (2) Moderate; (3) Severe; and (4) Extreme. Note that pilots may also report intermediate categories for turbulence intensity such as “light to moderate” as a way to bridge between two major categories.

Table 8. Turbulence intensity values and their definitions in the pilot reporting system as defined in the Aeronautical Information Manual (FAA, 2020).

Intensity	Aircraft reaction	Reaction inside aircraft
Light	"Turbulence that causes slight, rapid and somewhat rhythmic bumpiness without appreciable changes in altitude or attitude."	"Occupants may feel a slight strain against seat belts or shoulder straps. Unsecured objects may be displaced slightly."
Moderate	"Turbulence that is similar to Light Turbulence but of greater intensity. Changes in altitude and/or attitude occur but the aircraft remains in positive control at all times. It usually causes variations in indicated airspeed."	"Occupants feel definite strains against seat belts or shoulder straps. Unsecured objects are dislodged."
Severe	"Turbulence that causes large, abrupt changes in altitude and/or attitude. It usually causes large variations in indicated airspeed. Aircraft may be momentarily out of control."	"Occupants are forced violently against seat belts or shoulder straps. Unsecured objects are tossed about."
Extreme	"Turbulence in which the aircraft is violently tossed about and is practically impossible to control. It may cause structural damage."	Unspecified.

As mentioned earlier, the aircraft's weight class plays a critical role in determine the intensity of turbulence experienced by the aircraft. The International Civil Aviation Organization (ICAO) defines a broad category for weight classes (Table 9) to be "light," "medium" and "heavy" (Sharman & Pearson, 2017). That is, most aircraft in these broad categories will experience turbulence in the same way.

Table 9. The weight-class definitions as defined by the International Civil Aviation Organization (ICAO).

ICAO weight class	Weight limits (W) lbs
Light	$W \leq 15{,}500$
Medium	$15{,}500 < W < 300{,}000$
Heavy	$W \geq 300{,}000$

Lastly, the FAA/NWS provides a pilot with guidance (Table 10) on how to map turbulence to values of EDR and the appropriate aircraft weight class. Even though EDR is defined in a range from 0 to 1, it is more intuitive for pilots to use whole numbers instead of decimals. Therefore, in the application, users will utilize EDR*100 to create a range of possible values from 0 to 100. This table is based on the results in Sharman et al., (2014). Dr. Robert Sharman who was the lead author in the study provides this background in an email correspondence.

> “The idea was to compare PIREPs with in situ EDR data for the same report. But we only had [Boeing] 737 data for comparisons, and the spread was quite large, so we used the medians for comparison. Then we used a theoretical argument about aircraft response based on weight to expand the mapping to light and heavy aircraft. These have never been verified, and would be extremely difficult to do anyway without a lot of data that simply does not exist.”

Nevertheless, Table 10 documents the mapping used currently documented in FAA Advisory Circular 00-45H, Change 2 and will be utilized in the application.

Table 10. The aircraft class-specific thresholds as they relate to turbulence intensity and eddy dissipation rate (EDR * 100) as documented in FAA Advisory Circular 00-45H, Change 2 (FAA, 2016).

Weight class	**Light**	**Moderate**	**Severe**	**Extreme**
Light	13	16	36	64
Medium	15	20	44	79
Heavy	17	24	54	96

The GTG product offers three distinct forecast elements that include:

(1) Clear air turbulence (eddy dissipation rate)

(2) Mountain wave turbulence (eddy dissipation rate)

(3) Combined (eddy dissipation rate)

The combined turbulence is simply the highest EDR value between the clear air and mountain wave turbulence forecast for any particular grid point level. GTG is described in FAA Advisory Circular 00-45H, Change 2. This makes GTG optimal given that many pilots are currently familiar with this forecast guidance.

The GTG dataset becomes available on NOMADS every hour at prescribed times and arrives on NOMADS in a collection of several GRIBv2 files at flight levels from 1,000 to 45,000 feet MSL (in increments of 1000 feet) that are downloaded and processed over a period of ~20 minutes. These are downloaded and converted to geoJSON format at a 13 km resolution to replace the previous GTG dataset in the MongoDB. The GTG guidance provides a 1 h, 2 h, 3 h, 6 h, 9 h, 12 h, 15 h and 18 h lead time with each hourly execution. Similar to other guidance used in this research, the top of the hour is used as the reference time for this turbulence forecast. It is assumed that the weather forecast persists from the valid time at the top of the hour to the valid time for the next available forecast hour.

4.7.5.6 Determination of clouds

When flying above or below a well-defined cloud deck, it would appear that being in-cloud or out-of-cloud is a binary situation. From that observational perspective, it is. However, accurately forecasting the multitude of various cloud layers and cloud types that can co-exist along a given route is an enormous challenge. Even with a perfect NWP forecast, extracting the relevant information to effectively depict how clouds will evolve is challenging, especially when the clouds have significant vertical development and conditions are changing rapidly. Hence, choosing an appropriate cloud scheme to accurately predict the cloud cover, ceiling height and the cloud layer depth is important.

The various NWP models generate continuous forecast variables (e.g., temperature) on a three-dimensional grid with a specific horizontal resolution, or grid spacing, at various geopotential heights for specific lead times. Any proposed route will thus cross through a portion of these grid columns during flight. Therefore, to extract along-route weather conditions from a given model forecast requires knowledge of distance, altitude, and duration (time).

Even with the grid spacing of a few kilometers in the finest-resolution NWP models, cloud formation and evolution are often dependent on physical processes that occur at sub-grid scales (Wood & Field, 2000). Moreover, clouds exhibit quasi-discrete boundaries. When the cloud cover is more homogeneous (e.g., widespread stratocumulus deck) and saturated conditions prevail over a large area, multiple grid boxes will accurately exhibit an overcast "cloudy" condition (i.e. cloud coverage is represented accurately throughout multiple grid cells). However, in regions of highly variable weather (e.g. during a frontal passage) the sky cover at a single altitude can range from clear to partly cloudy to overcast within a single grid cell depending on its size.

Clouds are not explicitly predicted by most deterministic models. Rather, relative humidity has historically been the most-relevant ubiquitous meteorological element provided by models. As such, numerous relative humidity-based approaches to identifying clouds or cloud layers have been developed, but no definitive approach exists.

The most common approach is to use a monotonically increasing function of relative humidity, as first described by Sundqvist (1978) and Slingo (1980), and combined with the vertical velocity. As humidity increases to some critical value, confidence that rising air may be saturated at that geopotential altitude increases. For example, when the humidity is high (e.g., 95-100%), confidence is high that saturated conditions and overcast cloud cover is present at that altitude. Conversely, when the humidity is low (e.g., below 60%), confidence is high that no clouds exist at that level.

The NBM currently uses such a monotonic function (Figure 10) for determining the lowest cloud base (LCB). The NBM function exhibits a quasi-linear relationship, whereby the critical relative humidity threshold varies with atmospheric pressure, but other functional forms and thresholds have been used (e.g., Gordon 1992). Likewise, various specialized versions have been developed for specific scenarios. For example, CIP uses a humidity-based scheme to determine the presence of cold/mixed-phased clouds above the boundary layer (and thus the potential for aircraft icing); given an environmental temperature below 0°C, if the relative humidity exceeds an altitude-specific threshold, then clouds and aircraft icing are considered likely (Bernstein, et al, 2005).

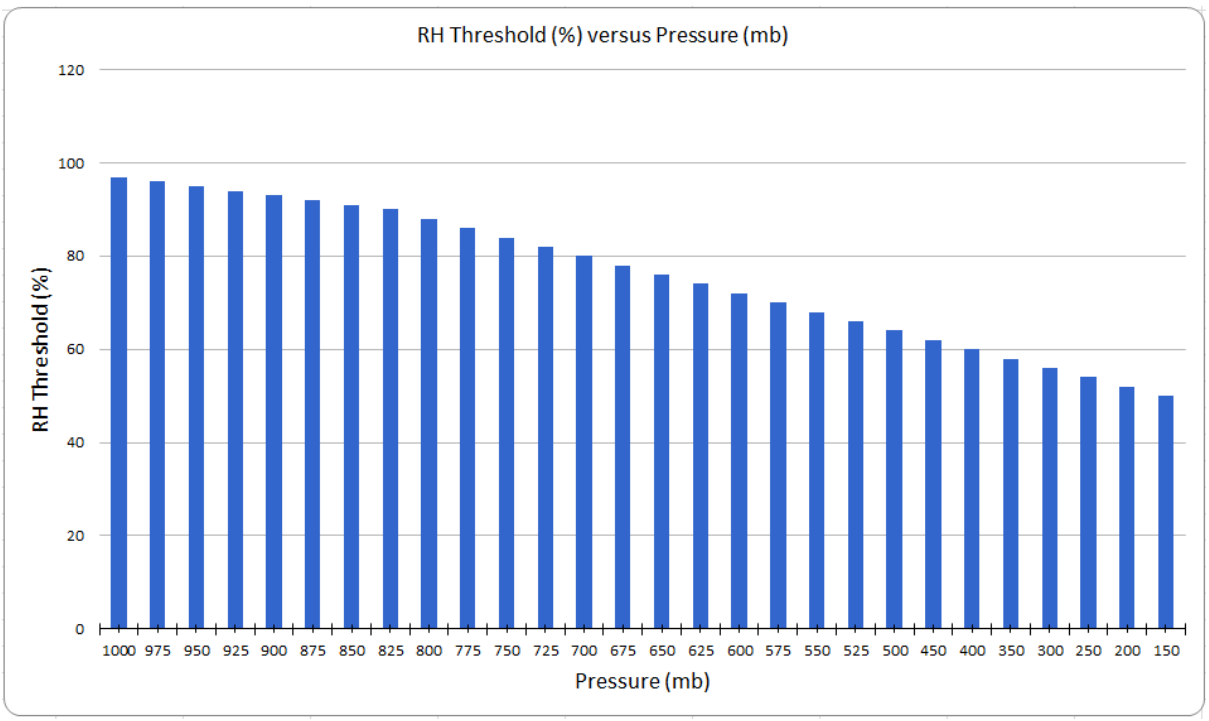

Figure 10. Relative humidity thresholds as they relate to pressure levels used to determine the National Blend of Models lowest cloud base[24].

[24] Values for this graph provided through email communication by Jeffrey Craven, Statistical Modeling Division (SMD) branch chief, National Weather Service, Meteorological Development Laboratory (MDL).

All of the humidity-based approaches ultimately denote each model grid box as either cloudy or clear, with no intermediate options for partial cloudiness. Several other limitations exist. For example, it is common for no clouds to exist even when the relative humidity exceeds the threshold for cloud determination, especially in the planetary boundary layer (McDonough, et al., 2003). Moreover, the presence or absence of clouds depends on many additional inter-related factors including temperature, static stability, vertical velocity, and the specific synoptic situation such as precipitation (Gordon, 1992). Finally, additional challenges can result from variable model resolutions, poor characterization of land surface variability within the model domain, and large uncertainties in the observed relative humidity used to initialize the models (Gultepe, 2019).

The "all-or-nothing" humidity-based approaches are simple to implement but they do not account for the cases of partial cloudiness within a grid box (i.e., sub-grid scale cloud variability) that often exists (Sommeria & Deardorff, 1977). For such cases, a different approach is warranted. One promising new method uses the grid box cloud fraction (ranges from 0.0 to 1.0, with 1.0 indicating 100% cloud coverage), which is explicitly predicted by many modern NWP models, including the mesoscale RAP model. In fact, the Aviation Weather Center (AWC) has recently moved away from the humidity-based approaches in favor of the cloud fraction scheme used in the Graphical Forecasts for Aviation (GFA) guidance (Figure 11), a replacement for the aviation area forecast that was retired on October 10, 2017 (NWS2, 2017). Moreover, such a cloud fraction scheme could be used along a route corridor to determine both the sky coverage and cloud layer heights.

Based on email correspondence from, Stephanie Avey, a research meteorologist at the AWC –

> "Our initial goal is to develop layers from the model that can be used in the Digital Aviation Services (DAS) paradigm by forecasters at the local offices. The resultant layers are then used to derive the cloud information (base, top, coverage, etc.) for the GFA. This allows the logic to be model agnostic, and creates consistency across the products."

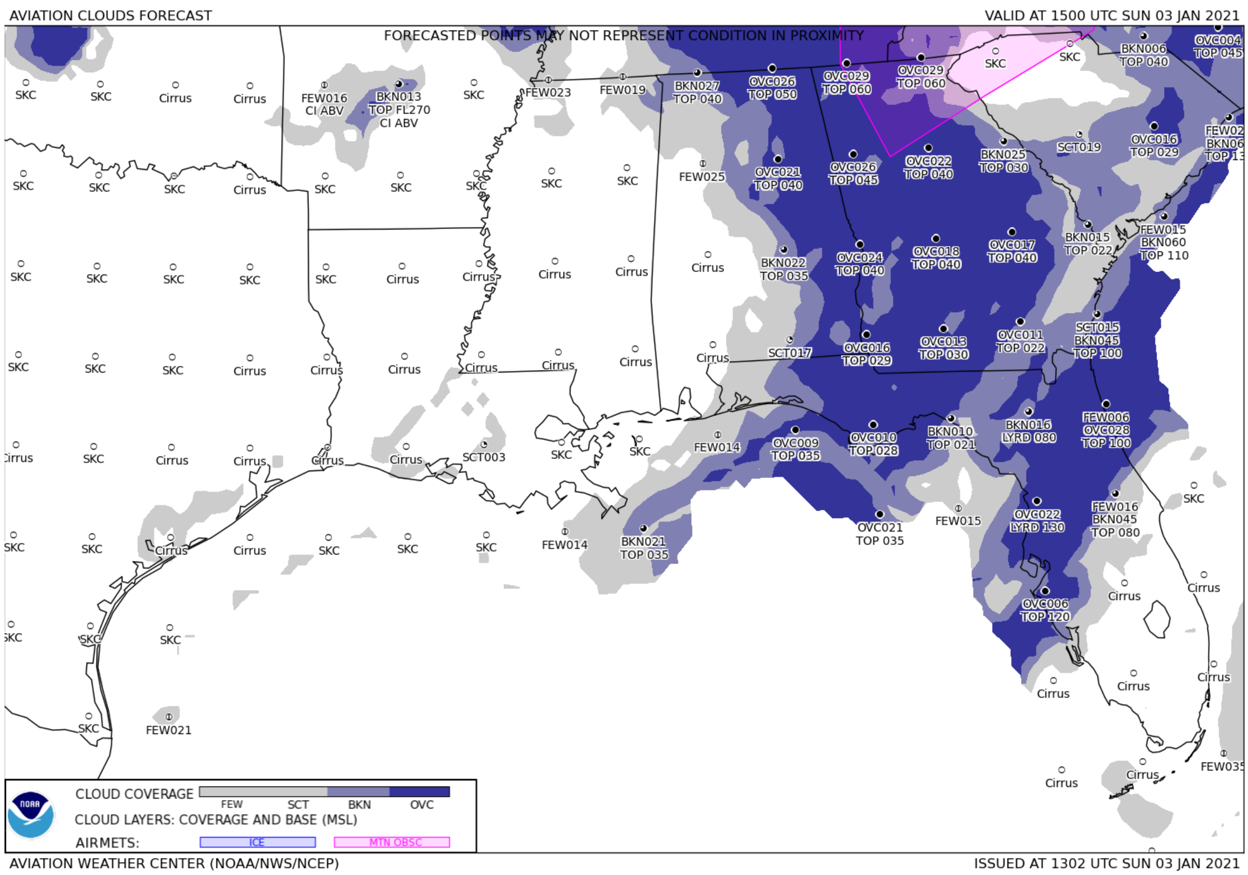

Figure 11. The Graphical Forecasts for Aviation (GFA) Southeast U.S. clouds depiction provided by the Aviation Weather Center that shows bases, tops, layered clouds and cloud coverage. See https://www.aviationweather.gov/gfa/plot.

The AWC scheme described here uses the High Resolution Rapid Refresh (HRRR) model to identify cloud tops, cloud bases, and fractional cloud coverage (Table 11) for up to three cloud layers in each grid column (Avey, et al., 2018). First, all cloud layers are identified within the column as instances when the cloud fraction exceeds 0.125 (or 12.5%) for a given model level. In the example given in Figure 12, a total of four cloud levels have been discovered at a particular model grid point. Next, starting at the surface and moving upward, distinct cloud layer breaks are identified as instances when the cloud fraction is less than 0.125 at least *two* consecutive model levels. This process is repeated up to 25,000 feet AGL, defining all cloud layer bases and tops through the layer. Any cloud *bases* detected above 25,000 feet are treated as cirrus clouds. The “primary” cloud base layer defined as the *lowest* broken (BKN) or overcast (OVC) coverage with a cloud fraction greater than 0.625. For the example, this is the layer denoted by (1). Also secondary and tertiary layers denoted by (2) and (3), respectively, may be identified. If no primary broken or overcast exists, then the lowest base is identified as scattered (SCT) or few (FEW). From this primary cloud base, the maximum fractional cloud coverage for the layer is identified.

Table 11. Cloud fraction amounts used to define the primary, secondary and tertiary cloud base used to define cloud layers for the Graphical Forecasts for Aviation (GFA) (Avey, et al., 2018).

Categorical coverage	Cloud fraction amount (CF)
Broken (BKN)	CF ≥ 0.625
Scattered (SCT)	0.375 > CF ≥ 0.625
Few (FEW)	0.125 > CF ≥ 0.375
Clear (CLR)	CF ≤ 0.125

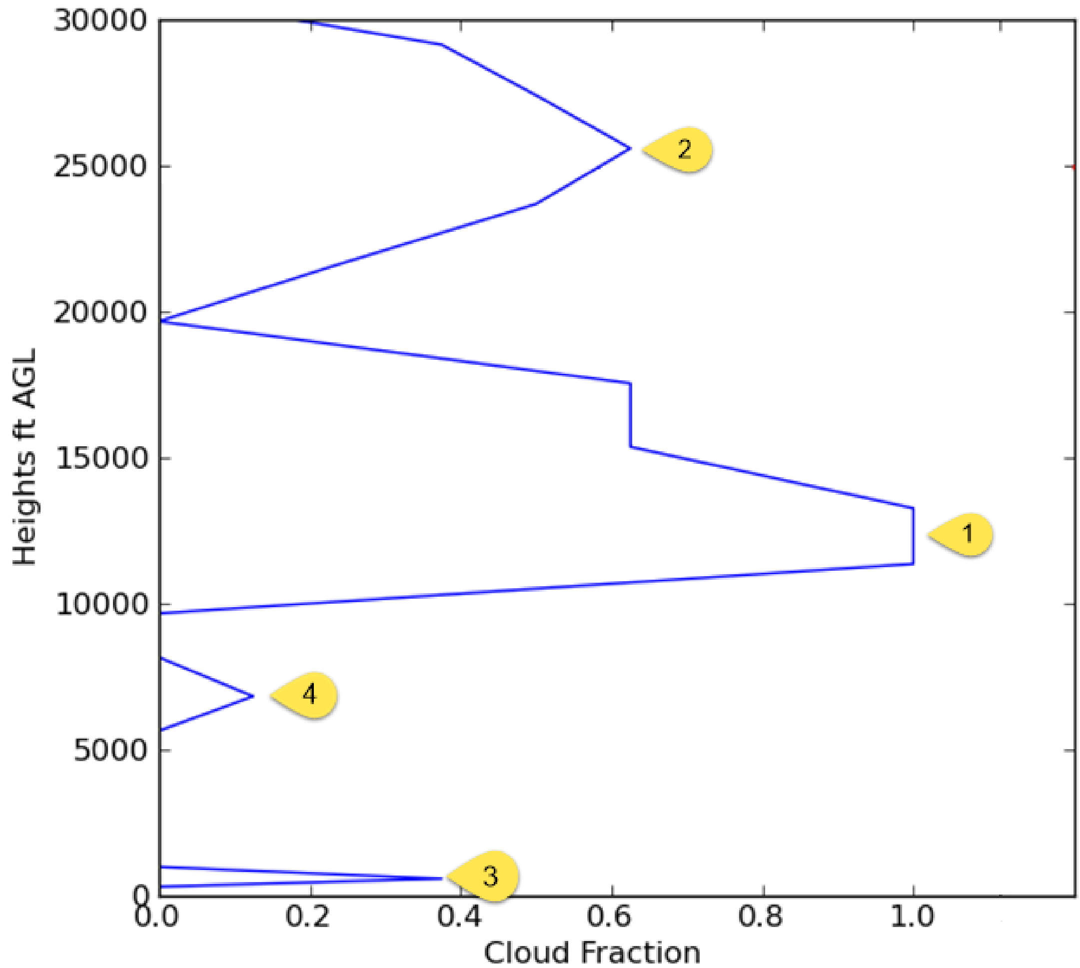

Figure 12. This shows an example using cloud fraction from the High Resolution Rapid Refresh (HRRR) model to identify the height of multiple cloud layers within a given grid column. In this example, four layers are discovered at a particular model grid point, however, only three are kept with the layer denoted (4) being discarded.

The cloud fractions scheme works well to automatically generate the GFA product for the AWC on an hourly basis. Essentially the GFA is focused to forecast the cloud base and cloud top height and whether the clouds are simply layered in between. For example, the magnified area in Figure 13 shows a specific point forecast to have a few clouds at 1,800 feet MSL and an overcast cloud layer at 3,000 feet MSL with layered clouds to the tops at FL350 (flight level 35,000 feet MSL).

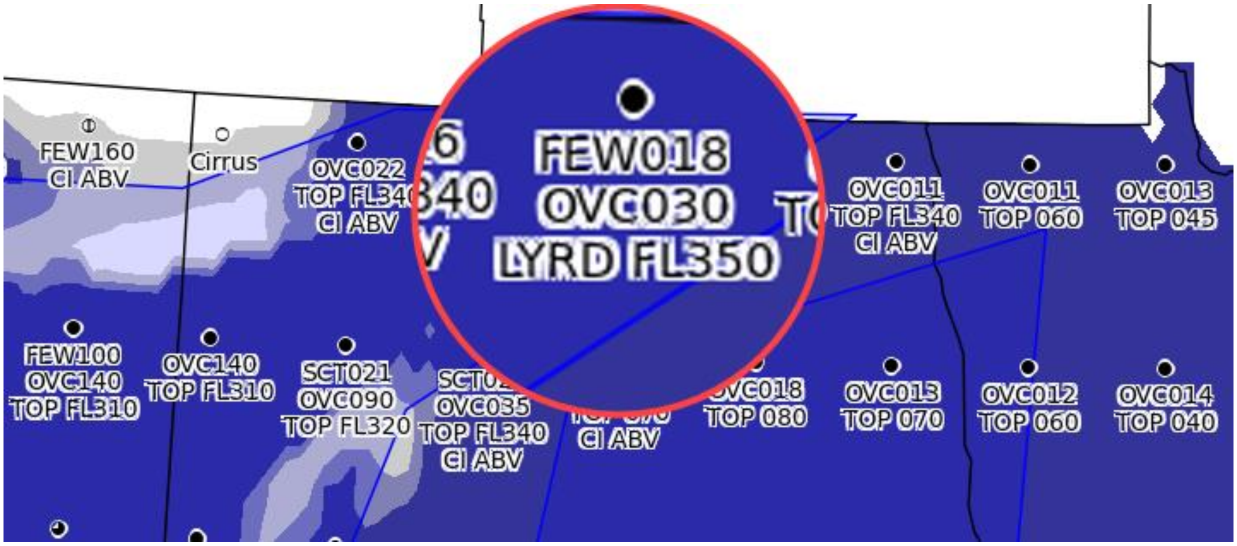

Figure 13. The Graphical Forecasts for Aviation (GFA) clouds forecast covering the north-central United States.

This cloud fractions scheme employed by the GFA is a bit limiting for creating a vertical route profile where there are potentially more than three cloud layers. Moreover, the GFS model does not provide cloud fractions so a quasi-linear monotonic relationship of relative humidity to the model pressure levels (Figure 10) is being used for this research. The depth of the cloud layer once the threshold is exceeded is essentially assumed to extend to half the vertical distance to the next layer above or below. It is then iterated from the top of the atmosphere at 150 mb down to the surface to identify the presence of clouds over a particular point along the proposed route of flight. Once the cloud layers are identified using this scheme, the NBMv4.0 cloud coverage nearest the same point will be used to determine the fraction of the sky that is covered. According to an email correspondence with Grant Hicks who is the Aviation and Assistant Graphical Forecast Editor (GFE) Focal Point at the NWS WFO in Glasgow, Montana and subject matter expert in the NWS for this scheme he states,

> "Using relative humidity to determine clouds getting into subfreezing temperatures when the partial pressures of ice and water are different is somewhat dubious. What I can say is that the relative humidity threshold decreases as you rise up in the atmosphere which can

> roughly account for this, but even then it is a crude representation which could be wildly off at higher levels. It does however, seems to work up to roughly 12,000 feet and has a semi-accurate rating above from qualitative analysis."

The depiction and determination of cloud heights along a route of flight is a critical aspect of this research. For situational awareness while en route, pilots need to be given an accurate assessment of IMC conditions. This has led to a significant effort to ensure the datasets used are consistent.

4.7.5.7 Meteorological consistency between datasets

Much of this research is not only driven by using specific datasets to represent and evaluate weather hazards and risk for a particular route of flight, but also how to appropriately combine them. Therefore, a major component that created its own challenges was determining an appropriate way to blend the forecasts. When depicting two or more independent datasets on a particular display, there is always a risk of inadvertently creating meteorological inconsistencies. For example, the depiction of visible moisture (e.g., clouds) along a route of flight has to address cloud coverage as well as the height and depth of cloud layers. This will require the use of the NBM for (1) ceiling height, cloud coverage and lowest cloud base (LCB) and (2) the cloud depth will come from the GFS model.

In fact, even within a particular homogeneous dataset there can be inconsistencies at times. For example, it was discovered during early testing that the NBM ceiling height and associated cloud coverage were sometimes inconsistent. This was verified with the NBM core blend technical lead, Robert James, who stated,

> "We have a consistency check in place to change ceilings to an unlimited value if sky cover is less than 57%. Where the sky cover is greater than 57%, but the ceiling is unlimited, we don't have any scientific method of setting a ceiling in that scenario, so we left the original forecast untouched."

The result of this inconsistency caused the application to depict an unlimited ceiling height with the sky coverage of broken or overcast. Moreover, adding additional complexity, the NBM also provides a forecast for the height of the LCB. The NBM LCB is, by definition, a cloud deck with a categorical coverage of scattered or few clouds. With an unlimited ceiling, the sky coverage forecast of less than 57% defines a LCB with a categorical value of scattered or few (Table 12) based on the percent coverage.

To avoid this inconsistency, the following was implemented. In the event the NBMv4.0 forecast a LCB along with an unlimited ceiling height, the sky coverage of 57% or greater was reset to 56%. This allows the application to process the cloud deck as a scattered layer. If no LCB was forecast in this case, the ceiling height is accepted as unlimited, and the sky cover is effectively ignored.

Table 12. The categorical cloud coverage and associated percentage of sky cover and black and white symbol.

Category	Coverage (%)	Black & white symbol
CLR (clear)	0-6	
FEW (few)	7-31	
SCT (scattered)	32-56	
BKN (broken)	57-87	
OVC (overcast)	88-100	

In order to provide a comprehensive and accurate depiction of the weather along the entire route of flight, much attention has been paid to keep a meteorological consistency between the datasets when combined on a display and for the evaluation of the weather along the proposed route of flight. The four datasets chosen for this research do have some inter-relationships worth mentioning.

While the NBM forecast is a blend of many different models, surface visibility forecasts for the departure airport, destination airport and along the route of flight will come from the NBMv4.0 gridded forecast and airport tabular bulletin. For cloud coverage and ceiling height, NBMv4.0 simply uses the forecast from the previous run of the Gridded LAMP (GLMP) through first 36 forecast hours for ceiling height and surface visibility. Given that the GLMP is derived from the GFS MOS model and that both the NBMv4.0 and GFS model have an hourly forecast resolution, significant inconsistencies between the derivation of clouds from the GFS humidity scheme and the NBMv4.0 cloud forecast are generally minimal. A three-pass method is used to eliminate any inconsistency that may arise.

In the first pass, cloud layers in a particular column of air above the surface will be determined using the GFS model's relative humidity scheme as discussed earlier. It is possible at times for no clouds to exist even when the humidity exceeds the threshold for cloud determination, especially in the boundary layer (McDonough, et al., 2004). This may happen when the clouds are producing precipitation and moistening the lower atmosphere. Therefore, the GFS model forecast is used during the first pass to locate the primary altitudes where clouds are likely to exist.

The second pass (Figure 14) is performed to eliminate the chance of discrepancies that lies between the clouds and icing depictions. That is, airframe icing is most likely to occur in regions where the sky coverage is broken or overcast (Bernstein, et al., 2005). Therefore, even after the first pass is performed, is it is still possible that the GFS might not predict clouds at heights where FIP predicts an icing environment. As stated earlier, the RAP is the model post-processed by the FIP algorithm. This sets up the possibility where the GFS and RAP may disagree, at times, with the location and height of clouds, specifically clouds that may contain supercooled liquid water. When that condition occurs, this pass will add cloud layers where FIP indicates icing probabilities that are greater than or equal to 10%.

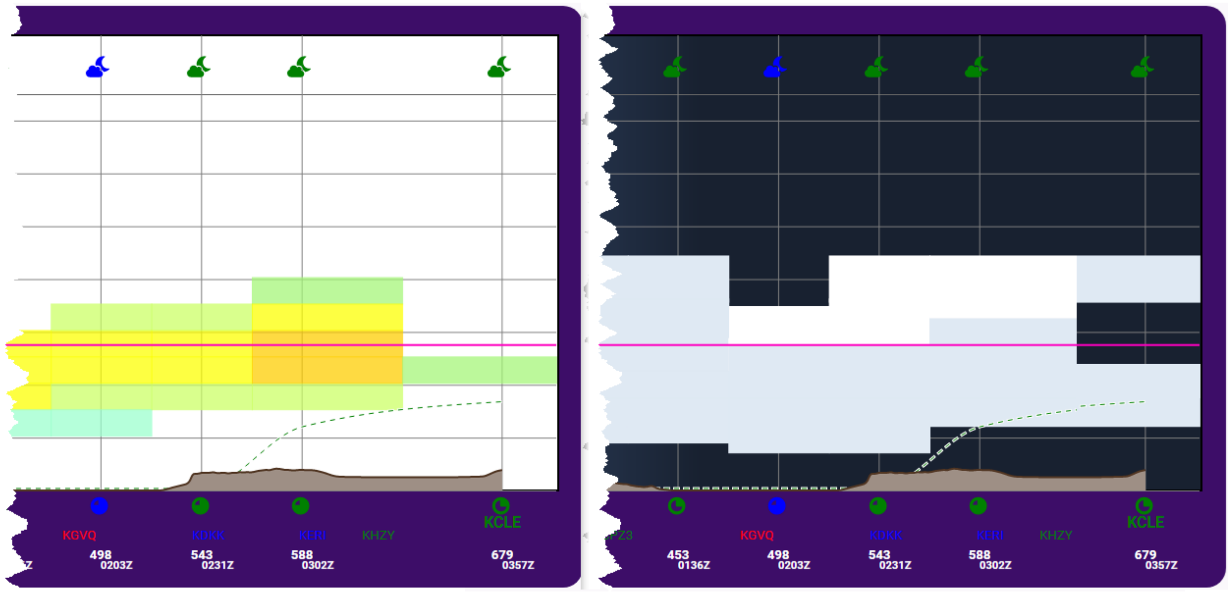

Figure 14. Side by side comparison of the icing (left) and cloud (right) depictions.

The third pass (Figure 15) leverages the NBMv4.0 forecast to (1) eliminate any clouds identified in the first and second pass below the NBMv4.0 ceiling height forecast and (2) determine the coverage (few, scattered, broken or overcast) of the clouds in the column since the GFS model cannot provide the sub-grid scale variability.

The first and second pass identified the likelihood that clouds exist in the column. In the example in Figure 15, the NBMv4.0 is used in the third pass to define a scattered layer at 11,100 feet and a broken cloud layer at 12,000 feet and eliminates any clouds below the lowest cloud deck that may have been added by the first two passes. The result is adding a gray box signifying a scattered cloud deck that is 11,100 feet above the terrain in the column (red arrow) and a white box signifying a broken cloud deck at 12,000 feet above the terrain (yellow arrow) in that column. Any other clouds at higher altitudes are retained as a broken coverage show by white boxes.

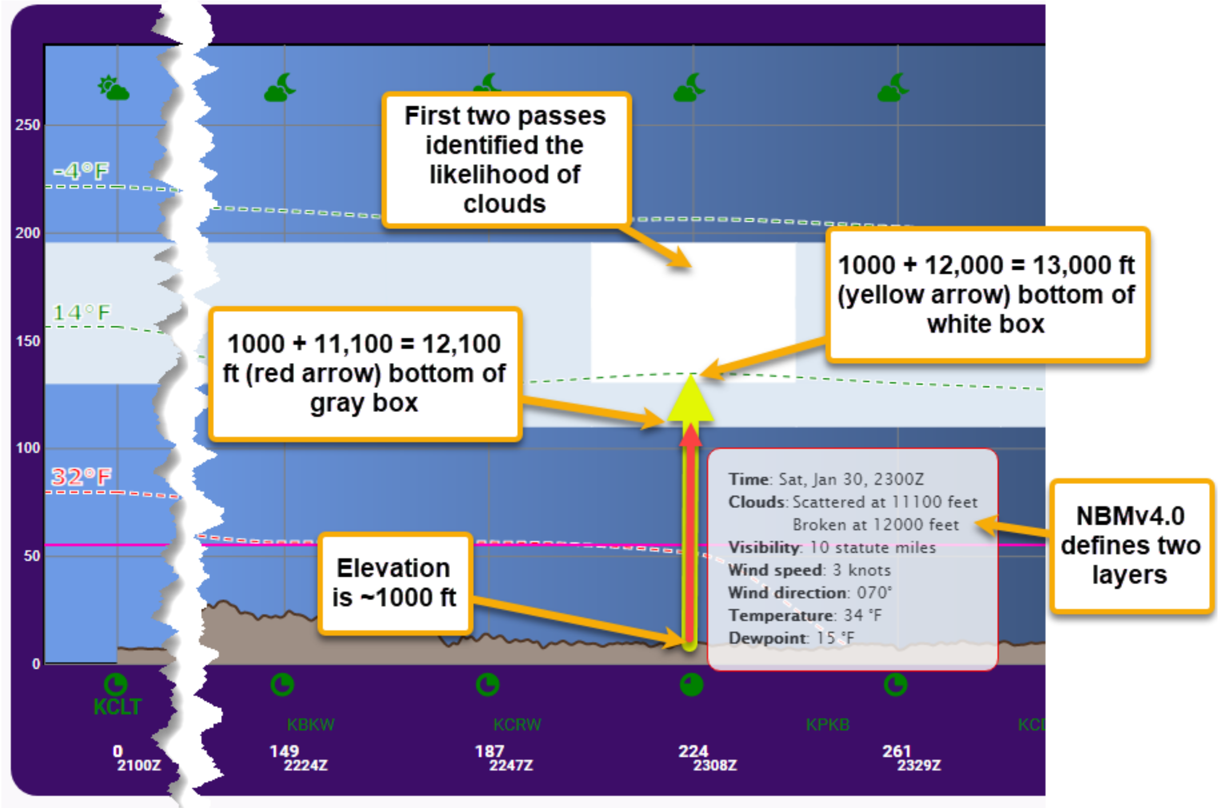

Figure 15. Cloud depiction results after the third pass showing a broken cloud deck (white) with a scattered cloud deck (gray) below for a specific column.

Moreover, it is also important to consider the scenario (Figure 16) where the GFS humidity thresholds are not met for cloud determination in the column, but the NBMv4.0 cloud forecast indicates otherwise. In this event, the NBMv4.0 ceiling height and/or LCB will be given precedent to depict a thin layer cloud event at the heights forecast for the column and colored depending on the cloud NBMv4.0 coverage. In the example in Figure 16, the first and second pass did not find clouds, but the NBMv4.0 indicated a scattered cloud layer at 10,500 feet existed. This requires adding a gray box signifying a shallow scattered deck and that is 10,500 feet above the terrain within the column.

Lastly, if the NBMv4.0 indicates that the cloud coverage is less than 7% (Table 12), the sky is deemed to be clear (e.g., no clouds exist in the column). All clouds will be eliminated in this column even if the first two passes identify the likelihood of clouds. While unlikely, this could create an inconsistency between the clouds and icing depiction.

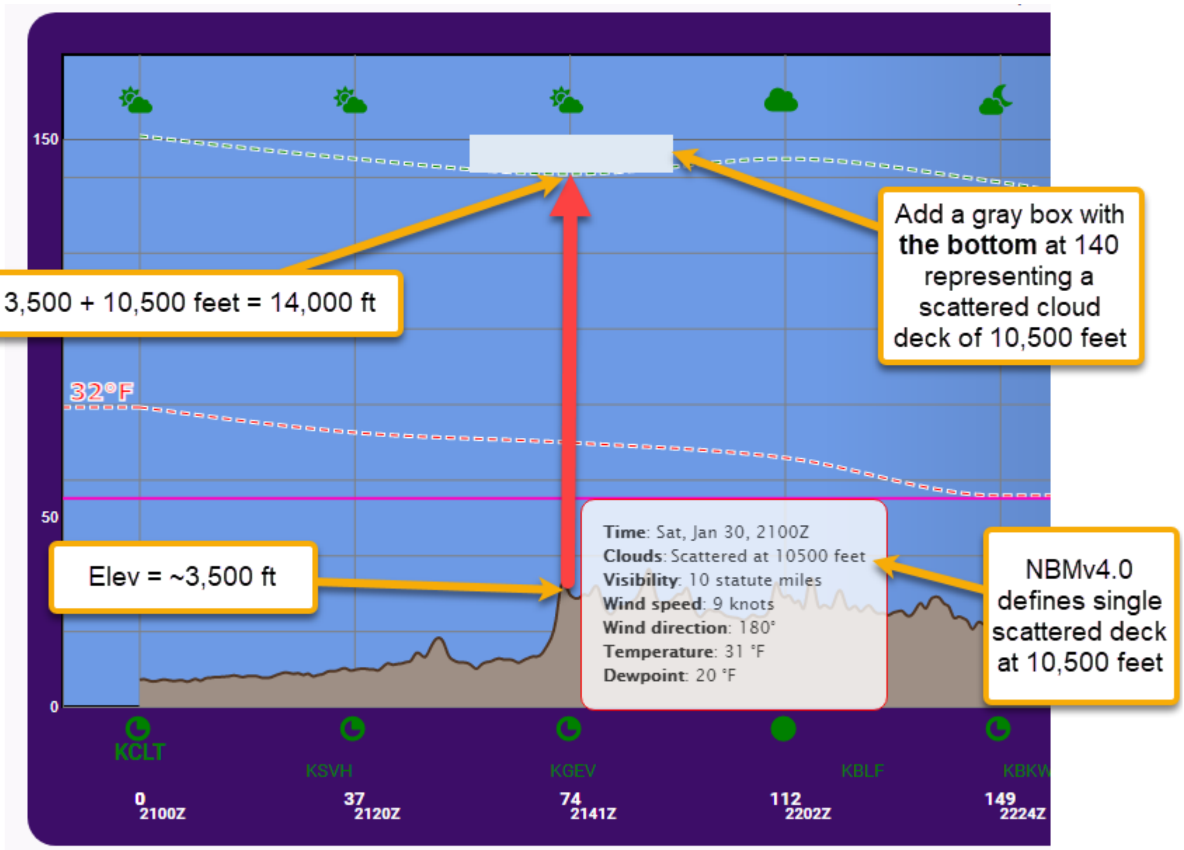

Figure 16. Example of how the third pass adds a scattered cloud deck not depicted by the first two passes. This applies to sky coverage values of few, scattered, broken and overcast.

The NWS introduced the RAP model in 2012 and the High Resolution Rapid Refresh (HRRR) mesoscale model in 2014 (Benjamin, et al., 2016). The RAP/HRRR is a deterministic forecast model that is executed hourly and is considered to be the newest long-term operational mesoscale model for use by the NWS. While not a requirement for input to a statistical scheme, the HRRR model computes explicit forecasts for both ceiling height and visibility for lead times from 1 h to 15 h (Benjamin, et al., 2016). Consequently, it became an advantage to blend the ceiling height and visibility forecast from the HRRR with the LAMP ceiling height and visibility forecast to produce the LAMP/HRRR "meld" to improve LAMP forecasts that currently used by the NBMv4.0 (Glahn, 2018). This newest improvement to the MOS system, referred to as the LAMP/HRRR meld, became operational on April 3, 2017 (NWS1, 2017).

Given that NBMv4.0 uses the LAMP/HRRR meld (Figure 17) forecast for ceiling height, this gives some peripheral relationship to the NBMv4.0 forecast and the forecast from FIP for the first 15 forecast hours. While this is not a perfect match, when a discrepancy exists at a particular location and height, the second pass attempts to add clouds aloft where FIP is indicating a 10% or greater chance of airframe ice, but will never add clouds below the NBMv4.0 forecast ceiling height simply due to a chance of airframe icing. If FIP produces an icing environment below the ceiling height this likely implies a precipitation event (e.g., freezing rain). In this case, the ceiling height is not modified to add lower clouds, but the icing depiction will be retained to show the icing threat below the cloud base.

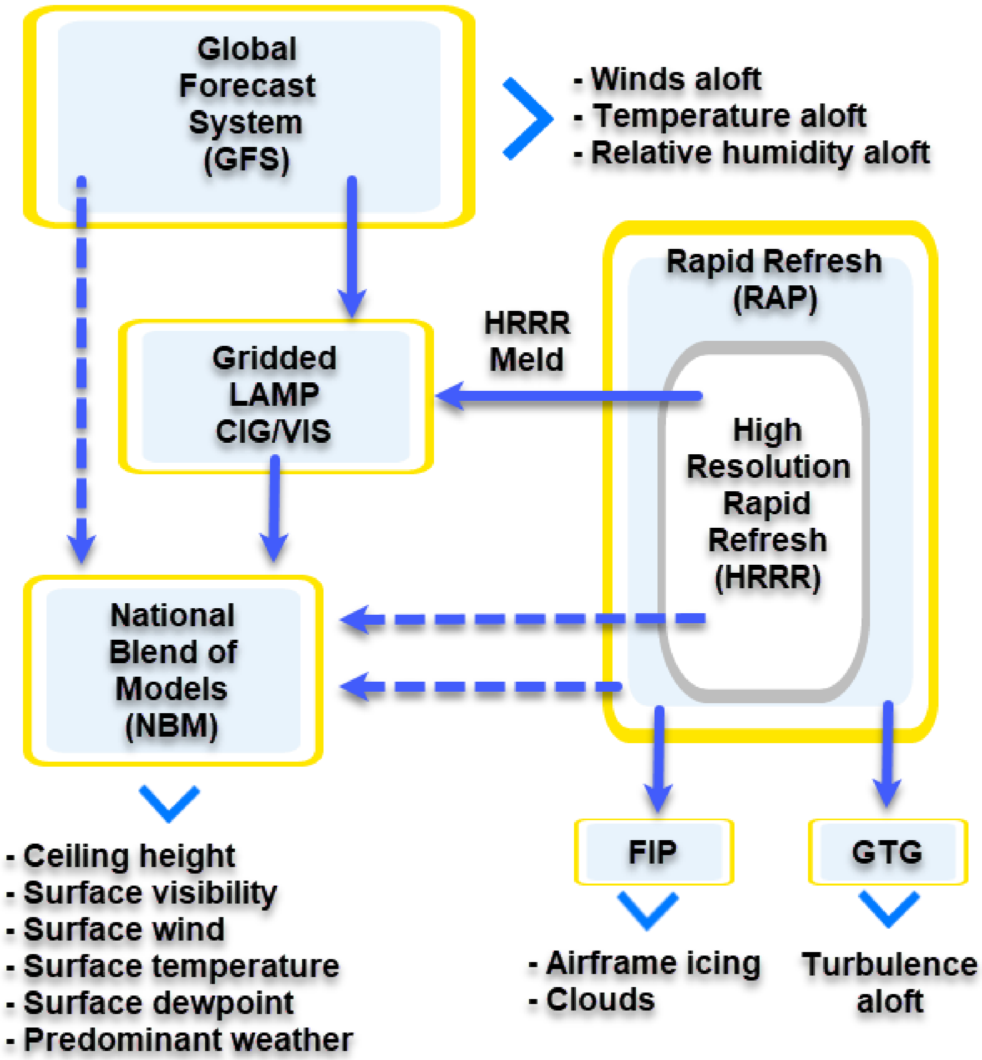

Figure 17. This defines the dataset inter-relationships within the application. Solid blue arrows represent a direct dependency. Dashed blue arrows represent an indirect dependency through the NBMv4.0 blend.

A route of flight consists of a departure and destination airport with optional “flyover” waypoints along the route. These optional waypoints are airports or other navigation waypoints available in the application’s navigation database. The application divides the route (Figure 18) into multiple great circle equidistant segments based on the total length of the route[25]. From this, the application applies the weather forecast (e.g., ceiling height, surface visibility, etc.) using the

[25] Longer routes will have longer segment length. Shorter routes will have shorter segment lengths.

"nearest neighbor" method executed through a geoNear function provided by the MongoDB application programming interface (API). The nearest georeferenced grid point in each of the respective datasets is chosen as a representation of the forecast weather based on the time of arrival for each segment endpoint.

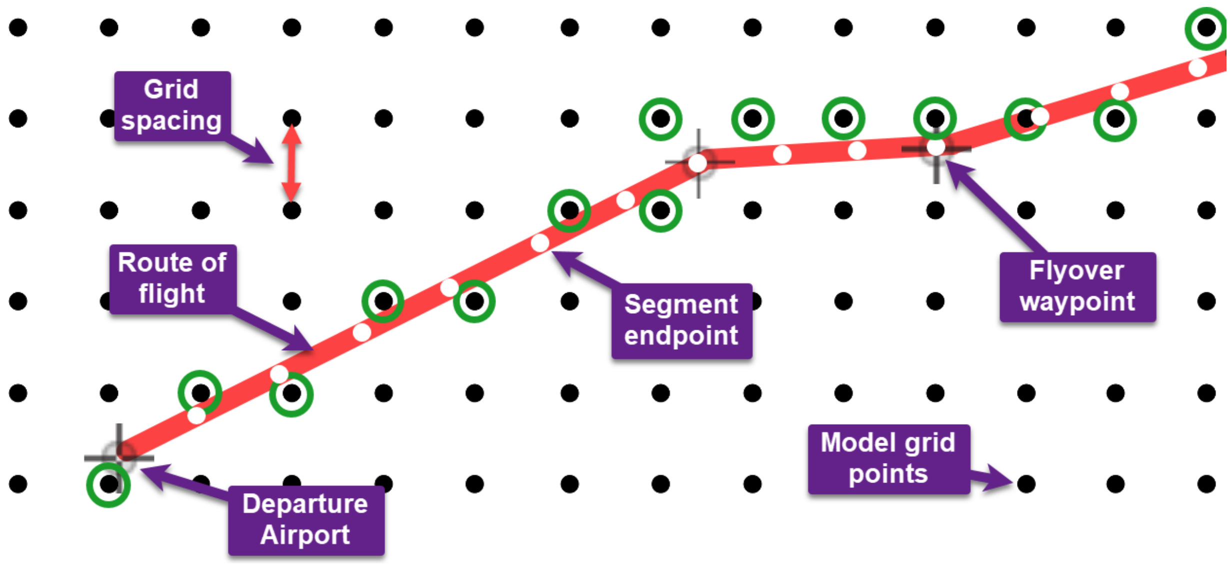

Figure 18. Route of flight (red) with segment endpoints (white) with underlying georeferenced dataset (black dots) and nearest neighbor (green). Note that each dataset has a unique resolution. Not drawn to scale or resolution.

The next dimension to consider is time. As stated earlier, the datasets have a temporal resolution of one hour where the top of the most recent hour is used. The time of departure of the planned flight will always be deemed to be at the top of each hour. To determine the time of arrival at each segment endpoint, the performance of the aircraft is determined by the planned true airspeed (TAS) decided by the pilot[26]. In order to determine the time of arrival at each segment endpoint, the ground speed (GS) must be calculated based on the planned TAS and factoring in the speed and direction of the forecast winds aloft based on the chosen time of

[26] This is stored in the applications aircraft settings.

departure. The climb and descent profiles and the departure and arrival flight paths are not factored in for this research[27].

The GFS model provides the east-west (***u***) and north-south (***v***) components of the wind. The closest model level is chosen to represent the forecast winds for the planned altitude[28]. The application iterates over each segment beginning at the departure airport to determine the GS by adding (or subtracting) the tailwind (or headwind) component to (from) the TAS. Next, using a simple time-speed-distance calculation[29] and the length of the segment, the GS is then used to determine the time of arrival at the next segment endpoint. This time of arrival is used as the beginning time to calculate the GS for the next segment. This is repeated for each segment until the last segment endpoint's arrival time at the destination airport. Therefore, the time of arrival at each segment endpoint can be determined. The application also allows for a "no wind" calculation simply using the pilot's planned TAS.

Lastly, and perhaps most importantly, this calculation is repeated for all possible departure times (at an hourly interval) over the next 2-3-day period. This provides the unique time-based capability referred to as the departure advisor to be described later. It is this feature that provides the most favorable time to depart based on the evaluation of the pilot's personal weather minimums. A pilot is more likely to choose a time that meets all of their personal weather minimums keeping the flight at most conservative level of risk. This also sets up the pilot to know the best time to depart when making a call to Flight Service when obtaining an official weather brief.

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[27] For most GA flights, the distance covered during a climb to or descent from cruise altitude will be located within the first segment of the route.
[28] The application incorporates a subset of pressure levels provided by the Global Forecast System (GFS) model. The GFS model also provides the geopotential height of that pressure level. From this, the nearest pressure level's wind data is chosen to calculate the ground speed based on planned altitude.
[29] time = distance/speed.

4.8 Summary of data and methods

Through a literature review of weather-based aviation accidents in the United States and a survey of GA pilots this research aimed to define a standard set of personal weather minimum for pilots. A survey with short answer questions and questions using a four-point Likert scale was distributed to a sample of ~7,000 GA pilots who fly light fixed-wing aircraft within the United States to obtain a better comprehension of the importance of personal weather minimums. A total of 1,123 responses were received and compiled for this research.

After the completion of the survey, participant responses were compiled and categorized to create a better comprehension of the importance of personal minimums for GA pilots within the United States. The results included personal weather minimum categories for ceiling height, surface visibility, surface wind, airframe icing potential, turbulence potential and convective potential.

An online software application was designed, in part, based on the results of the survey and literature review. The application consists of seven primary capabilities: (1) collect and store various online weather forecasts and aeronautical data; (2) collect and store data from the user for aircraft-specific settings; (3) collect and store data from the user for personal weather minimum settings; (4) allow user to define, edit and store a route of flight; (5) evaluate personal weather minimums against forecast weather data along user-defined route for future departure times; (6) display the results from the risk assessment in an easy-to-consume manner; and (7) organize and display to the user weather forecasts to increase situational awareness along the proposed route of flight. Four primary forecast datasets were chosen as the foundation for the application's weather data including: (1) Global Forecast System (GFS), (2) National Blend of Models (NBM), (3) Forecast Icing Product (FIP), and (4) Graphical Turbulence Guidance (GTG) product. The domain for these datasets covers the conterminous U.S. and coastal waters as well as portions of southern Canada and northern Mexico.

CHAPTER 5: RESULTS

Responses to the list of survey questions initially developed in this dissertation assisted in the creation of a list of personal weather minimum categories. After completion of the survey, those results were tallied and then used to develop a subset of personal minimum categories determined to have the highest level of significance for evaluation during pre-flight planning within the targeted application.

5.1 Survey results

There were 1,123 pilots that responded to the survey within the allotted time and all responses were considered in this research. Below is a discussion of respondents' answers as they relate to the short answer and demographic questions.

5.1.1 Demographic questions and summary of responses

(1) What pilot certificate do you currently hold (student, private, commercial, ATP)?

and

(2) Are you instrument rated?

In the group of pilots surveyed, no respondents were student pilots[30] with 47% of pilots holding a private pilot certificate, 37% holding a commercial pilot certificate, and 16% holding an airline transport pilot (ATP) certificate. Of these, 75% indicated they were instrument rated. The number of instrument rated pilots in the survey aligns closely with those FAA statistics (Table 13) for 2019. The respondents with ATP certificates are less than half of those in the pilot population. The respondents surveyed are primarily general aviation pilots whereas the FAA statistics include both GA and professional pilots certificated in the United States. ATP

[30] The survey required that respondents must hold at least a private pilot certificate to participate.

certificates are not typically sought after by most general aviation pilots unless there's a desire to become a professional pilot or advance their skillset beyond the commercial certificate.

Table 13. Estimated active airmen certificates held in the United States by certificate category and instrument ratings as of December 31, 2019 (data extracted from https://www.faa.gov/data_research/aviation_data_statistics/civil_airmen_statistics).

Category	Number of certificates held	% of total (excluding student)
Pilot total	**638,828**	**N/A**
Student	**197,665**	**N/A**
Private	**161,105**	**36.5**
Commercial	**100,863**	**22.8**
Airline Transport	**164,947**	**37.3**
Rotorcraft (only)	**14,248**	**3.2**
Total w/o student	**441,163**	**N/A**
Instrument ratings	**314,168**	**71.2**

(3) How many total flight hours have you logged?

and

(4) How many years have you been a pilot?

The average number of years of experience from the respondents was 9.7 years with the lowest at 2 years and the highest at 52 years. The average number of hours logged as a pilot (includes flight time as a student pilot) was 1,950.7 with a minimum of 220 and a maximum of 19,300. The FAA does not publish specific data on years of experience or hours flown for comparison purposes.

(5) Do you regularly fly an aircraft with a certified ice protection system (IPS)?

and

(6) If forecast, what intensity of airframe icing is considered too risky (e.g., trace, light, moderate, heavy)?

For aircraft equipage, 8% of the respondents indicated that they fly a pressurized aircraft and 13% said they fly an aircraft with a certified ice protection system (IPS). It is worth noting that most pressurized aircraft also have a certified IPS installed. An aircraft without a certified IPS cannot legally fly into known icing conditions of any severity as documented on an aircraft placard in the cockpit and in the limitations section of the aircraft's pilot operating handbook (POH). Generally speaking, aircraft with a certified IPS are permitted to fly into a "small drop" icing environment[31]. For those respondents that fly an aircraft *without* a certified IPS, 92% said that it was too risky to fly into an icing environment purported to be of moderate or greater severity. That was in stark contrast to 79% of respondents that fly an aircraft with a certified IPS that stated it was too risky to fly in severe icing conditions. Consequently, the FAA regulatory guidance and aircraft equipage largely frames what pilots are willing to tolerate with respect to airframe icing.

(7) If forecast, what intensity of turbulence is considered too risky (e.g., light, moderate, severe, extreme)?

Unlike airframe icing, turbulence has no regulatory restrictions and the dangers of turbulence are often hard to quantify. Most encounters with turbulence are benign and it is often a matter of comfort. Nevertheless, 86% of respondents indicated that an environment that was purported to produce severe turbulence was too risky and 8% stating extreme turbulence was too risky.

(8) What is the average duration of your flights?

The endurance of a GA aircraft depends on many factors. Longer flights generally introduce a higher potential of crossing a frontal boundary and encountering adverse weather. However, it is not unusual for most GA pilots to plan a flight lasting four hours. Respondents indicated that the average duration of a cross-country flight was 2.7 hours. The responses ranged

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[31] According to FAA regulations, a "small drop" icing environment is one where the median volumetric diameter (MVD) of the liquid drops is less than or equal than 50 microns. If the MVD is greater than 50 microns, this is referred to as a supercooled large drop (SLD) environment. No aircraft has yet been certified into a SLD environment.

from 1.2 to 3.9 hours. The FAA does not record statistics for the length of flights for comparison. This research is focused on flights that have a duration of at least one hour, so this fits into the framework of the application being developed.

(9) What is the maximum crosswind component you feel comfortable landing at an airport with sufficient runway width?

and

(10) What is the maximum crosswind component you feel comfortable taking off at an airport with sufficient runway width?

All certified aircraft have a maximum demonstrated crosswind component documented in the aircraft's POH or aircraft flight manual. This is a maximum value which has been demonstrated by a test pilot to safely land the aircraft. However, the demonstrated maximum crosswind does not appear in the POH limitation section and is merely a suggestion for pilots to follow. Similar to turbulence, there are no regulatory thresholds provided by the FAA for landing or takeoff at an airport in excessive surface wind speeds. In other words, there are no regulations that prevent a pilot from landing in a crosswind that is higher than the maximum demonstrated crosswind for the aircraft. Nevertheless, if an accident did occur during a crosswind landing attempt that exceeded this threshold, the pilot could be cited for a careless or reckless operation of the aircraft. For landing, the respondent's average maximum crosswind was 17.4 knots with the minimum being reported at 10 knots and the maximum being reported at 32 knots. For takeoff, the average crosswind was 23.7 knots with a minimum of 13 knots and maximum of 42 knots. This is consistent with the fact that a takeoff in a strong crosswind can be difficult, but it is landing in such conditions that will add the most risk, especially for those pilots with little flight experience.

5.1.2 Summary of remaining responses

The following additional questions were posed to the respondents to address the overall importance of specific weather hazards. Below is a summary of the responses for each of those questions. Respondents were asked to rate their answers using a four-point Likert scale as follows:

(1) Not important

(2) Somewhat important

(3) Important

(4) Very important

(1) How important is having daylight to make a flight?

For the importance of flight during daylight hours, 86% of those surveyed indicated that it was very important with 10% responding that it was important. This is not surprising since it is often difficult to see weather (e.g. clouds) with enough advance notice at night especially in combination with poor flight visibility and mountainous terrain. According to a 2001 study by Capobianco and Lee, only 9% of weather-related GA accidents occur at night, but they almost always result in fatalities. Essentially, it is easier for a VFR pilot to miss cues at night and become disoriented especially when the weather is deteriorating (Weigmann et al., 2005). These results do not suggest the need for a specific personal weather minimum category for day versus night, but instead, when the flight is at night, more conservative weather minimums must be honored.

(2) How important is mountainous terrain when considering a flight?

and

(3) How important is departing out of or landing at an airport in mountainous terrain?

Originally published in 1963, the FAA has described (Figure 19) Designated Mountainous Areas (DMAs) in 14 CFR Part 95 Subpart B. These areas are documented in the Aeronautical Information Manual (AIM) and are regions where FAA minimums for standard instrument approach procedures and airspace definitions are treated differently. The primary concern is for obstacle avoidance such that pilots should adhere to a different set of more conservative minimums or rules in these areas.

Figure 19. Designated Mountainous Areas (DMA) for the conterminous United States and Puerto Rico are shown here in blue (FAA, 2020).

Therefore, it is no surprise that 77% of the respondents indicated that flying in a mountainous region was very important with 22% saying that it was important. Similarly, 83% replied that flying into or out of an airport in mountainous terrain was very important with 13% indicating it was important. It is clear from the accident data that a flight in mountainous terrain increases the risk substantially (Wilson & Sloan, 2003). In fact, the NTSB found during a survey of VFR into IMC accidents from 1975 to 1986 that eight of the ten of the U.S. states located in DMAs had the highest percentages (NTSB, 1989).

Similar to flight during daylight hours, these results do not require a specific personal weather minimum for flight into mountainous terrain, but suggests that if the flight originates, terminates or involves flying over mountainous terrain that more conservative weather minimums must be considered to reduce the overall risk especially as it relates to VFR flight.

(4) How important is the availability of weather reporting at the destination or departure airport?

and

(5) How important is having a weather forecast for surface visibility at the destination airport?

and

(6) How important is having a weather forecast for surface visibility at the departure airport?

and

(7) How important is having a weather forecast for ceiling at the destination airport?

and

(8) How important is having a weather forecast for ceiling at the departure airport?

Many airports in the United States offer weather reporting (e.g., observations) through the Automated Surface Observing System (ASOS) and Automated Weather Observing System (AWOS). Both of these systems provide the latest weather reports through a ground-to-air transmission using selected frequencies or through the telephone. This is done through a continuous automated broadcast to provide pilots with an overview of the latest weather for the airport's terminal area. The broadcast is generally updated every minute. The weather elements provided include temperature, dewpoint temperature, surface visibility, ceiling height, wind speed and direction and altimeter setting. The weather for the airport can also be obtained through satellite and ground-based systems that broadcast a subset of the latest weather reports and special observations to receivers in the cockpit. Nevertheless, these reports provide critical information for many operational decisions made by pilots (i.e., the best runway to use for takeoff or landing[32]).

Thus, 47% of the respondents indicated that having the availability of weather reporting at the departure or destination airport was very important with 35% indicating that it was important, but only 10% suggesting it was not important. This research is emphasizing forecast weather prior to flight, however, having access to the weather at the departure and destination airport remains important.

It is apparent from the survey that the ceiling height and surface visibility at the destination airport (Figure 20) is deemed as far more important than at the departure airport. This is, in part, similar to the old adage that says, "Takeoff is optional, landing is not." There are two points to consider. First, the weather at the departure airport prior to takeoff is clearly known based on the pilot's own observations and the latest automated weather observations. If the ceiling height or visibility is outside of the pilot's acceptable risk (i.e., does not meet their personal weather minimums) at the time of departure, the pilot can scrub the flight without hesitation. In other words, there are no risks to remaining on the ground. On the other hand, landing at the destination airport may be hours after the aircraft departs. While there may be recent observations at the time of departure, the pilot must still rely on a forecast. Because of

[32] This is defined as the runway with the maximum headwind component that meets other requirements (e.g., runway length).

this, the pilot sees landing at the destination as a greater risk, and therefore, important to know the expected weather.

Second, once in the air, the pilot must find a place to land if the weather deteriorates at the destination. Not being able to land at the destination airport because the weather is below the pilot's personal weather minimums means the pilot must either assume more personal risk to attempt to land or the pilot must search out an alternate landing location, preferably at an airport.

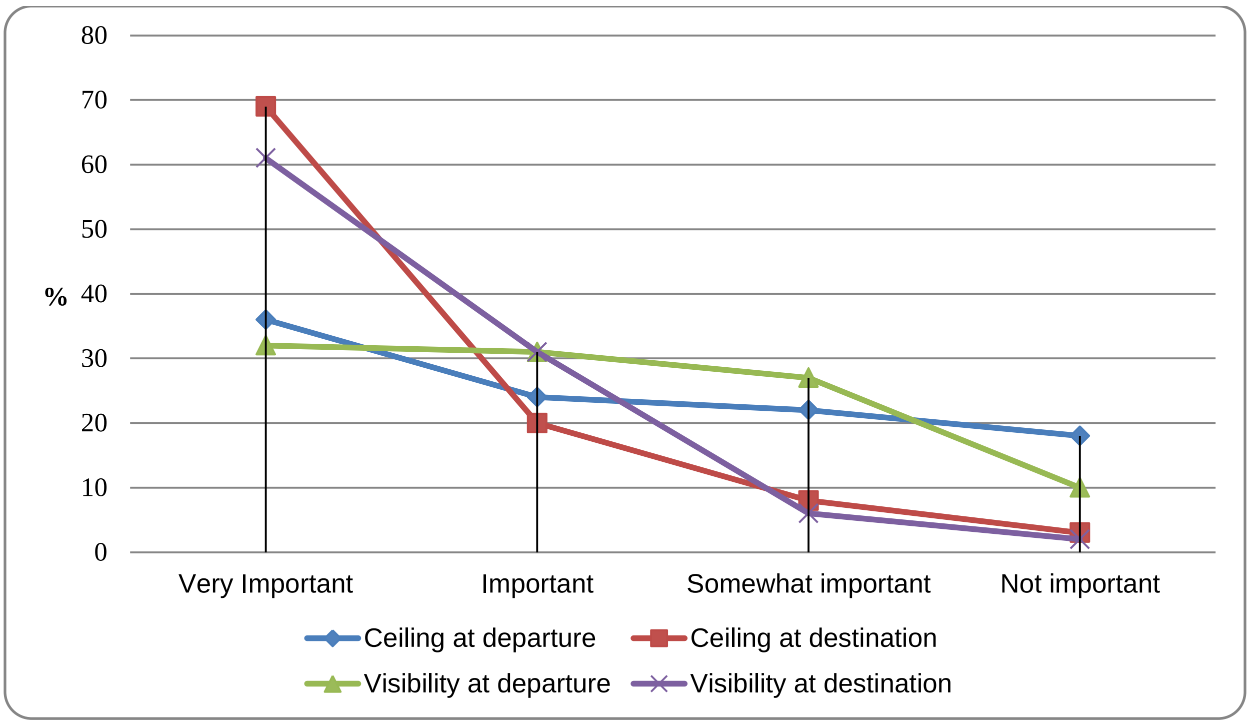

Figure 20. Importance of forecast ceiling height and surface visibility at the departure and destination airports based on the percentage of categorical survey responses.

(9) How important is having a forecast for ceiling along the route of flight?

and

(10) How important is having a forecast surface visibility along the route of flight?

For the forecast ceiling height and surface visibility (Figure 21) along the route of flight, the results of the survey were not as definitive. The level of importance is generally spread evenly. This is, in part, due to the differences in the flight rules being flown. Pilots who conduct a flight under IFR are required to fly at altitudes many thousands of feet above the terrain where surface visibility and ceiling height are not as important. Pilots flying under VFR, however, are permitted to fly as low as 1,000 feet above the terrain and have a greater concern for weather near the surface. Therefore, deteriorating weather due to reduced ceiling height and surface visibility are what often lead to a VFR into IMC scenario while en route. Given that 75% of the respondents indicated they were instrument rated, the results do align with this argument. Not specifically shown here, 67% of the respondents who were not instrument rated reported that having a forecast for ceiling height and surface visibility along the route was very important.

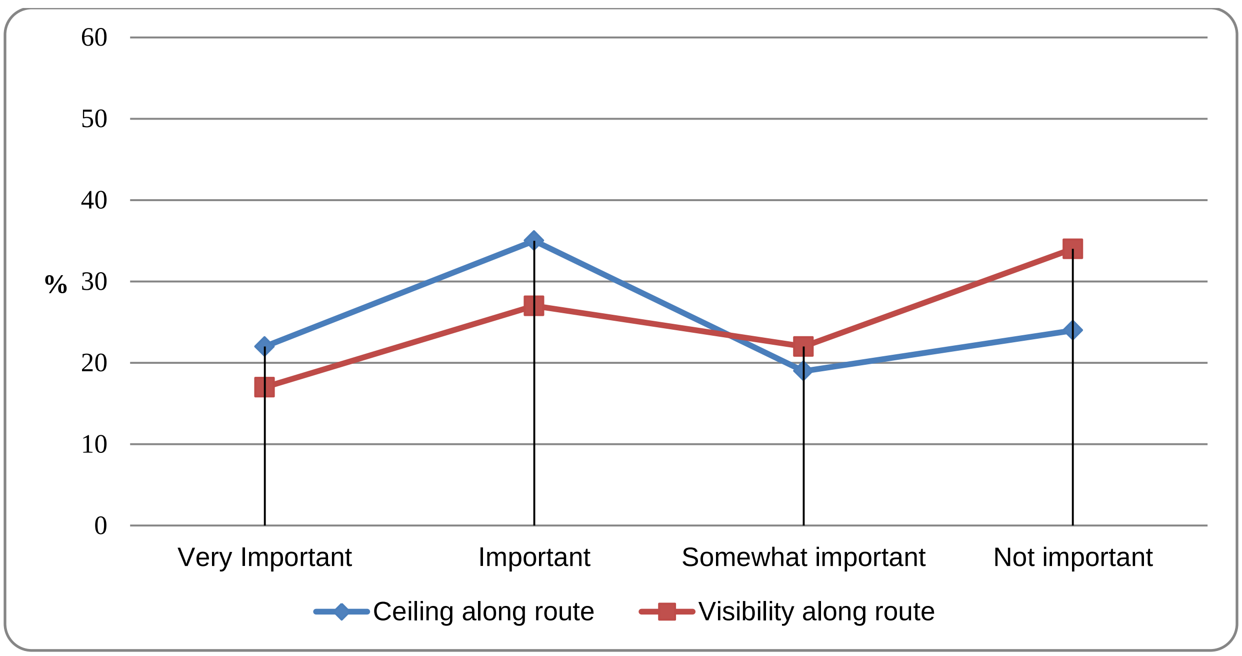

Figure 21. Importance of forecast ceiling height and surface visibility along the route of flight based on the percentage of categorical survey responses.

(11) How important is having a weather forecast for wind speed and direction at the destination airport?

and

(12) How important is having a weather forecast for wind speed and direction at the departure airport?

Wind is responsible for a majority of GA accidents, but has a low fatality rate[33] as compared to VFR into IMC or other loss of control accidents (AOPA, 2018). Having a wind forecast at the departure and destination airport is primarily concerned with (1) strong gusty winds and (2) significant crosswinds. When the wind is very well aligned with the runway heading, often in very strong sustained winds a takeoff or landing is not too challenging. The primary challenge is the amount of crosswind component.

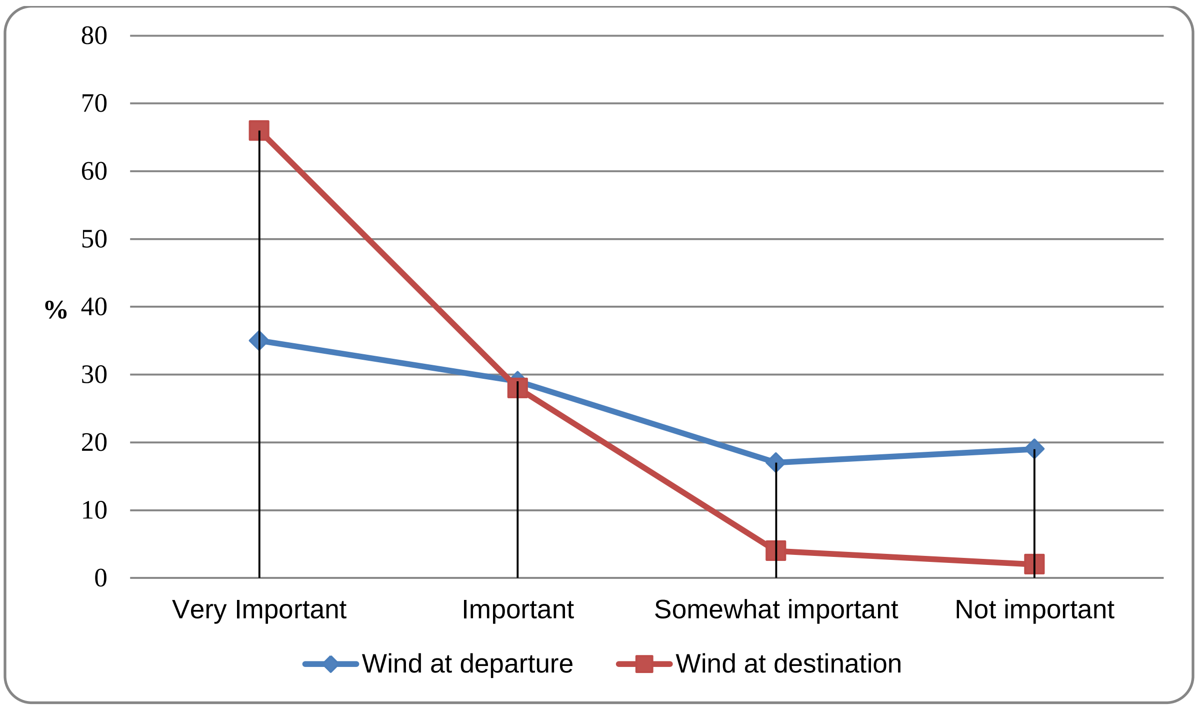

Figure 22. Importance of forecast surface wind speed and direction at the departure and destination airport based on the percentage of categorical survey responses.

A takeoff in a strong crosswind can be difficult, but landing in such conditions that will add the most risk, especially those pilots with little experience. With 35% of the respondents clearly indicating that having a forecast for surface wind at the departure airport is very

[33] This is largely because the aircraft are at a slower groundspeed during landing and takeoff creating a lesser amount of kinetic energy to dissipate.

important (Figure 22), 66% stated it was even more important to have a surface wind forecast available at the destination.

(13) How important is determining the likelihood of turbulence along the route of flight?

and

(14) How important is determining the likelihood of airframe icing along the route of flight?

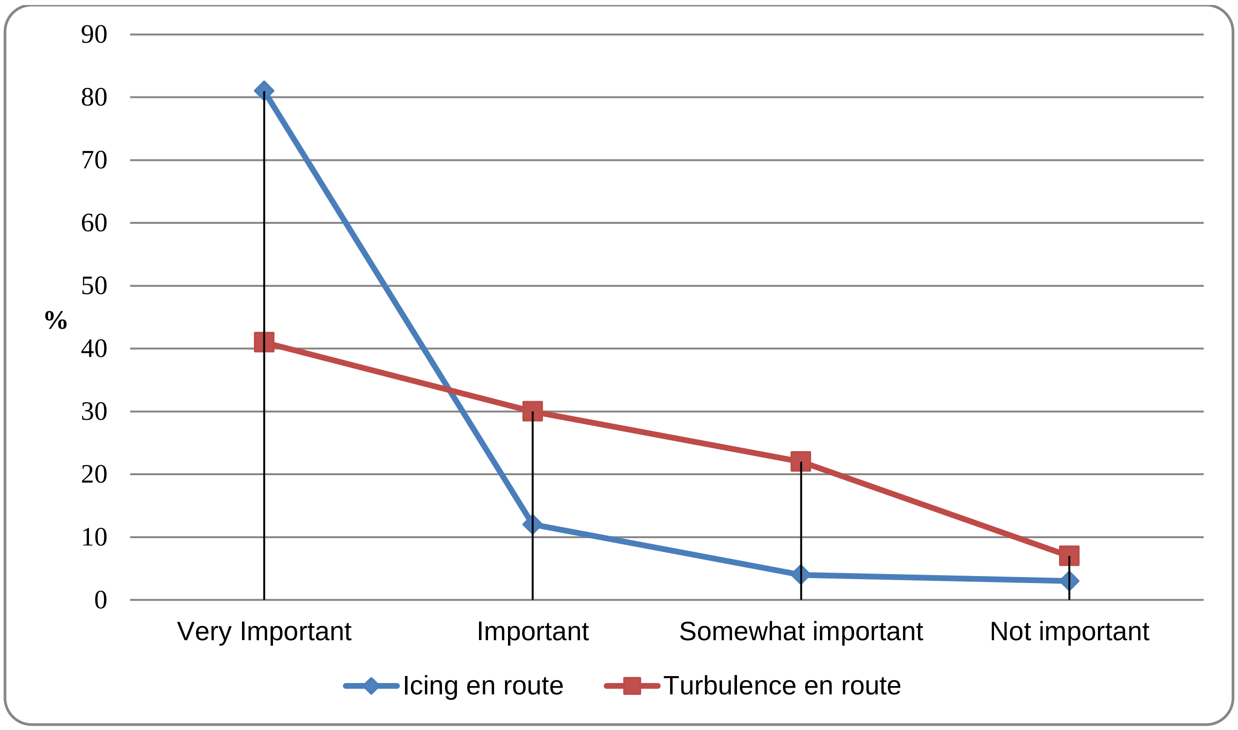

Figure 23. Importance of a forecast of icing and turbulence en route based on the percentage of categorical survey responses.

The number of yearly accidents due to airframe icing and turbulence are about half of the accidents that were attributed to VFR into IMC (AOPA, 2018). Nevertheless, turbulence and airframe icing accidents are often fatal. At 81%, respondents indicated (Figure 23) that having an icing forecast along the route of flight was very important with 12% suggesting it was important. Having a turbulence forecast along the route, on the other hand, was viewed to be not as important as a forecast for airframe icing, but 41% still indicated that it was very important with 30% responding as being important. As discussed earlier, there are regulatory repercussions when flying into known icing conditions. That is not the case with respect to turbulence. This is demonstrated quite well in the responses provided in the survey.

(15) How important is determining the forecast height of the lowest freezing level along the route of flight?

Given that airframe icing is highly unlikely when the static air temperature is warmer than 0°C, knowing the height of the freezing level along the route is important in choosing the proper cruise altitude. An altitude that puts an aircraft in visible moisture and at a static air temperature between 0°C and -25°C creates the potential for airframe icing (Bernstein, et al., 2005). For this, 91% of respondents agreed that it was very important to know the height of the lowest freezing level along the route of flight. This does not suggest a need for a specific personal minimum category for the lowest freezing level, but suggests that there is a need to depict the 0°C isotherm along the route for situational awareness.

5.2 Personal minimum category selection

The results of the survey and together with the literature review highlighted the need to define *twelve* key personal weather minimum categories as they are relate to ceiling height, surface visibility, surface wind, convective potential, airframe icing and turbulence. Given that accidents attributed to weather occur in all three phases of flight, it is apparent that personal weather minimums need to consider flights (1) departing an airport; (2) en route to an airport and; (3) landing at an airport.

In order to achieve overall improvement of the quality of weather assessment as compared to already existing technologies, this application satisfies the following conditions:

(1) Accept and store the personal minimum thresholds entered by the pilot;

(2) Evaluate the weather along the entire route of flight to determine if the weather meets or exceeds those thresholds for a specific time of departure;

(3) Display the results to the pilot in a way that is easy to interpret.

Personal weather minimums allow a pilot to set thresholds for each category based on their own personal risk assessment. These thresholds can be set by the pilot as needed based on the conditions of that flight (e.g., mountainous terrain, nighttime). Once a route is entered, the application automatically compares the appropriate forecasts along the proposed route for each personal minimum category defined to determine if the weather meets or exceeds the thresholds for all possible times of departure.

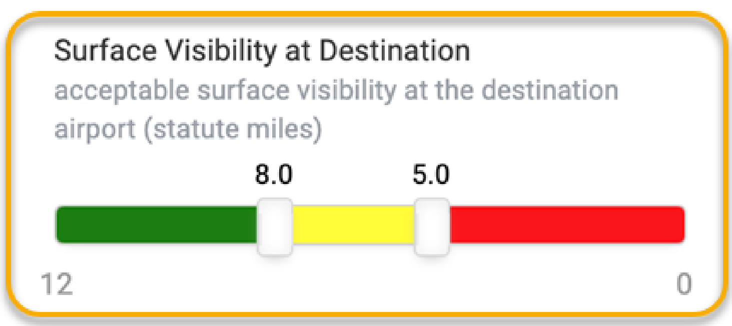

Figure 24. Example of a personal weather minimum category for the surface visibility at the destination airport.

The proposed approach uses a three-tiered categorical traffic light concept (green, yellow and red) to make the interpretation of the results easy for pilots. But first, the pilot must define two specific values for each personal minimum category. For example, the category being defined in Figure 24 is the surface visibility at the pilot's destination airport. The pilot is instructed to set the maximum and minimum threshold for green and red by sliding the white bars left and right accordingly. Green defines the threshold that the pilot perceives as a very low or conservative risk. At the other extreme, red defines the threshold that exceeds the pilot's acceptable risk (e.g., their personal minimum). Lastly, yellow is associated with moderate risk and represents the middle ground to exercise caution. The pilot can, however, assign a very narrow range to the moderate risk. Having such a three-tiered approach allows the pilot to define a healthy safety margin and a bias toward making a more conservative decision assuming the personal minimums are set appropriately by the pilot.

Many of the personal weather minimum categories contain "continuous" integer ranges such as surface visibility in statute miles with the minimum possible value set at 0 and the maximum possible value set at 12. This method also works well for those personal weather minimums that have a categorical construct that occur with convective potential, airframe icing and turbulence (e.g., light, moderate and severe).

It can be seen in Figure 24 that the pilot set **Green** to 8 statute miles and **Red** to 5 statute miles. With this, the pilot feels extremely comfortable (low risk) when the surface visibility at the destination airport is forecast to be 8 statute miles or greater at the estimated time of arrival (ETA) for this airport. On the other hand, the pilot feels extremely uncomfortable (high risk) when the surface visibility at the destination airport is forecast to be 3 statute miles or less at the ETA at the destination airport. The top end of the **Red** range (in this case 5 statute miles), is defined as the pilot's personal minimums for surface visibility at the destination airport. If the pilot is planning to arrive at 1800 UTC, for example, and the surface visibility is forecast to be 4 statute miles, this will likely result in a decision to stay, or alternatively, find a more appropriate time to depart or maybe fly to a nearby airport with better weather (e.g., a higher surface visibility forecast) at the time of arrival.

Once all of the personal minimums are set by the pilot and a route is defined, the application automatically evaluates the weather over a range of near-term departure times (i.e., within the next 2 to 3 days) and over all personal minimum categories for the proposed route.

This evaluation is encapsulated in what will be referred to as the “departure advisor” (Figure 25) since it advises the pilot of the risk along the proposed route as it relates to the time of departure. Any changes to the proposed route, weather forecasts or personal weather minimums will force the application to reassess and render a new depiction on the departure advisor. The departure advisor will be used in conjunction with the map and the vertical route profile views.

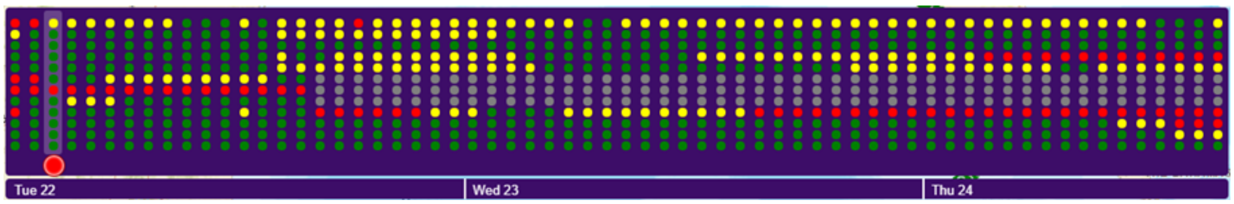

Figure 25. Presentation of the departure advisor for departures over the next two to three days using the traffic light concept. Time increases from left to right. Gray dots indicate that data was missing, and an evaluation could not be completed for the category at the specified departure time.

Each colored dot in the departure advisor (Figure 26) represents the evaluation of a specific personal weather minimum category for a specific time of departure. Therefore, each column of dots encompasses all personal weather minimum categories for a specific time of departure with time advancing from left to right. Each row represents a specific personal minimum category (e.g., surface visibility at the destination airport).

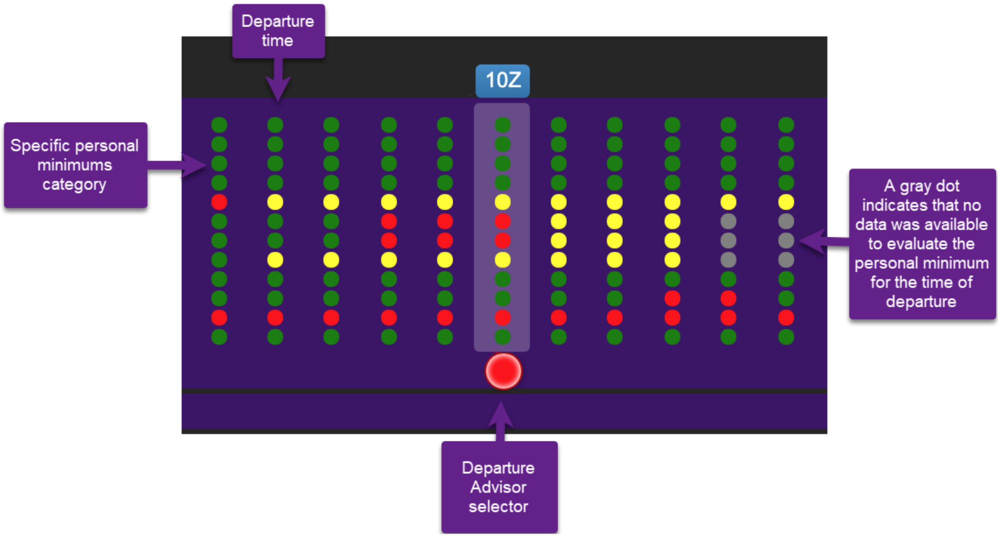

Figure 26. A close-up view of the departure advisor with rows representing the specific personal minimum category and columns representing a specific time of departure. Shown here is a departure for 1000 UTC.

This presentation creates a high glance value for the pilot to determine the departure time that creates the lowest (or highest) level of risk. In other words, a column that is entirely green suggests that all of the personal weather minimums in all of the categories have been met with a significant safety margin for a particular time of departure. On the other hand, if any of the columns exhibit one or more red markers, this means there are personal weather minimum categories that have not been met for the route, and therefore, elevating the pilot's personal risk for that departure time. A column with a mixture of yellow and green dots (Figure 27) tells the pilot to exercise caution given that the weather is approaching their personal minimums creating a moderate risk for those categories identified by yellow. As such, these features will aid in not only improving overall weather assessment for light fixed-wing aircraft and helicopter pilots through providing accurate risk predictions based upon weather forecast and personal minimum thresholds, but also enabling the prevention of weather-related accidents.

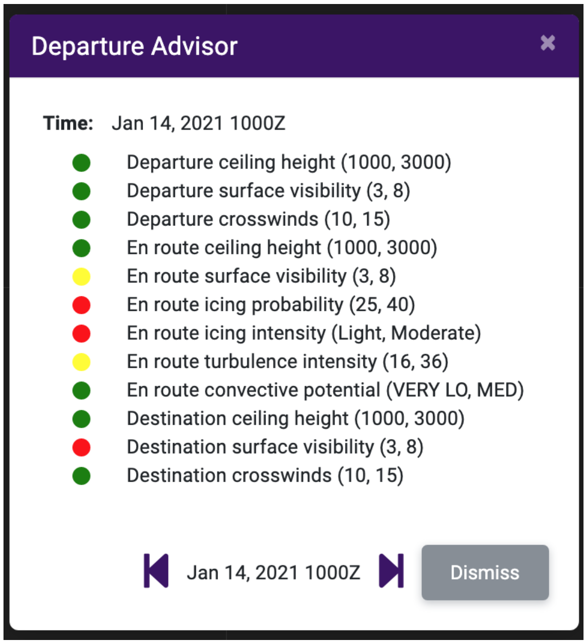

Figure 27. Evaluation of the results of all personal minimum categories based on a single departure time of January 14, 2021 at 1000 UTC. Items in parenthesis are a reminder of the current settings for the green and red thresholds assigned by the pilot for each category.

5.3 Personal weather minimum categories

A total of twelve categories were identified to allow the pilot to quantify the risk of any particular route of flight based on their own personal minimums. These can be further grouped into personal minimums for the departure airport, destination airport and along the route of flight to include –

(1) Ceiling height at the departure airport;

(2) Surface visibility at the departure airport;

(3) Crosswind component at the departure airport;

(4) Ceiling height along the route;

(5) Surface visibility along the route;

(6) Icing probability along the route;

(7) Icing intensity along the route;

(8) Turbulence intensity along the route;

(9) Convective potential along the route;

(10) Ceiling height at the destination airport;

(11) Surface visibility at the destination airport; and

(12) Crosswind component at the destination airport.

Table 14. Personal weather minimum categories with default risk thresholds and setting ranges. Turbulence intensity is expressed as Eddy Dissipation Rate (EDR) * 100.

Category	Maximum	Minimum	Green	Red
Ceiling at departure	6000 feet	0 feet	3000 feet	1000 feet
Visibility at departure	12 SM	0 SM	5 SM	3SM
Surface crosswind at departure	35 knots	0 knots	10 knots	20 knots
Ceiling at destination	6000 feet	0 feet	3000 feet	2000 feet
Visibility at destination	12 SM	0 SM	8 SM	5 SM
Surface crosswind at destination	35 knots	0 knots	10 knots	15 knots
Ceiling along route	6000 feet	0 feet	3000 feet	2000 feet
Visibility along route	12 SM	0 SM	8 SM	5 SM
Icing probability along route	100	0	20	10
Icing intensity along route	Heavy	None	Trace	Light
Turbulence intensity along route	100	0	16	36
Convective potential along route	Very High	None	Very low	Low

Upper and lower range limits for each personal minimum category and default settings were defined by combining the FAA regulatory guidance along with the survey results and literature review. This includes (

Table **14**) a maximum and minimum range of possible values for each setting as well as the default Red threshold (high risk) and the default Green threshold (low risk). These thresholds represent a starting point that is reasonable and appropriate for most GA pilots. Pilots can change these default settings at will based on their own personal risk tolerance for each category. When a route is defined, the application examines all of these personal minimum category thresholds against the forecast for the corresponding weather element.

For pilots making a VFR flight, the ceiling height and surface visibility personal minimums are the most critical. This includes those along the route and at the departure and destination airports. Pilots flying IFR will not be as concerned with ceiling and visibility along the route given that they are legally able to fly in IMC and are trained to do so. Moreover, the legal minimums to take off and land at an airport for a pilot operating under IFR are typically less stringent. Therefore, the personal minimum defaults for ceiling and visibility have been favored to support a pilot flying VFR or newly instrument rated pilot flying IFR.

5.4 Application architecture

All components within the application's system architecture (Figure 28) are hosted on the Amazon Web Services (AWS) computing platform. The application consists of two high level computing components. The first component is a scheduled batch process to download and store the required weather datasets and navigation data used by the application. The second component is a web-based application that authenticates users, manages user preferences and settings, accepts user-defined routes and displays maps containing weather and navigation data along with other visual representations of weather along the proposed route of flight as it relates to the time of departure.

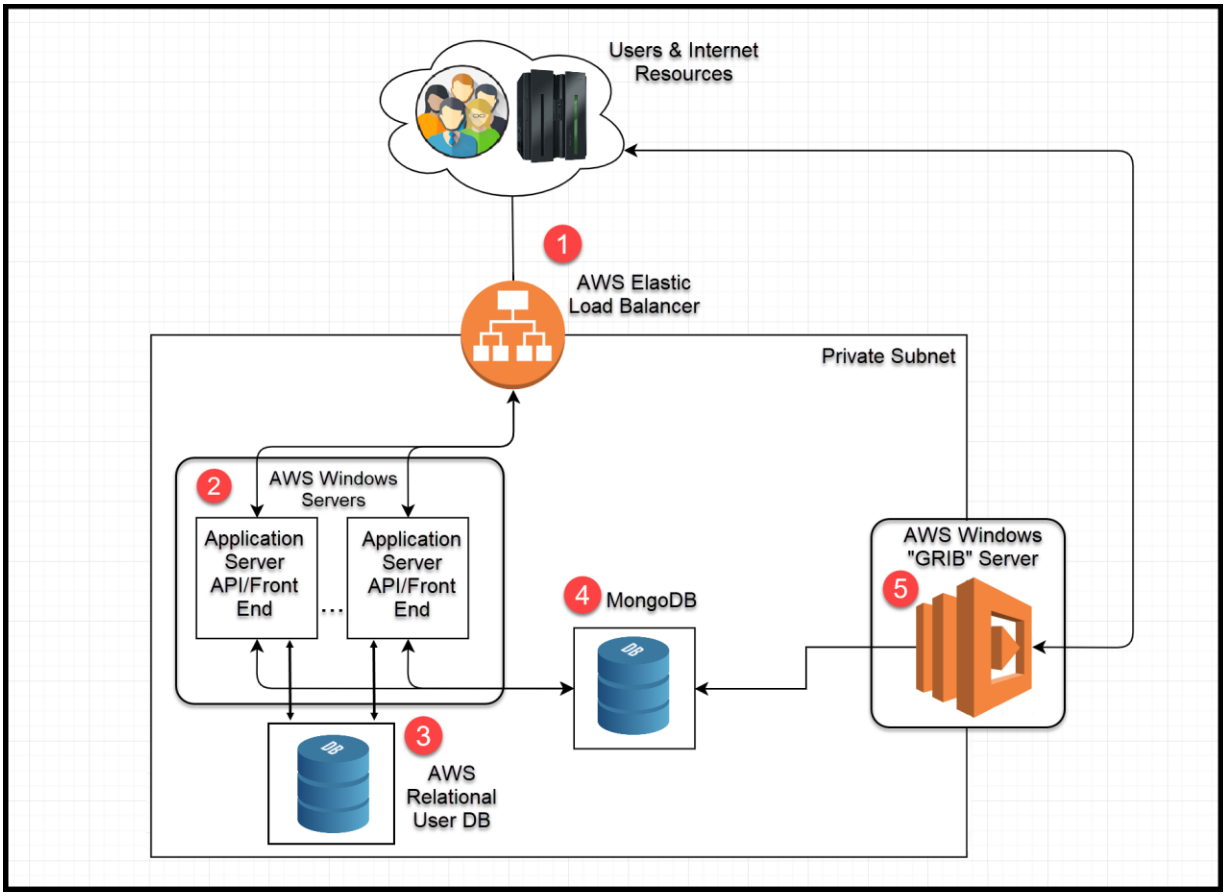

Figure 28. Overview of the primary components of the application architecture.

The interface between the user and the application is an AWS elastic load balancer denoted by [1] in Figure 28. As Internet requests from the user arrive, they are immediately routed through the load balancer. It is designed to monitor the health and current load of each Microsoft Windows Server instance in the cluster (denoted by [2] in Figure 28) and routes the request to a healthy instance that exhibits the least load.

5.4.1 Application software

The software running the web-based application is common across all instances and is written using a popular scripting or programming language called JavaScript. The application interfaces with a common AWS Microsoft SQL relational database denoted by [3] in Figure 28. This database stores information specific to each user such as their email address and password for authentication and session monitoring, their most recent route and various settings and preferences including the user's personal weather minimums. The application also interfaces with a single MongoDB (denoted by [4] in Figure 28) to retrieve the latest weather information used to evaluate the weather along the proposed route of flight against the user's personal weather minimums and to populate other displays for the purposes of situational awareness.

5.4.2 Batch processing software

All of the raw NWS datasets are stored in highly compact GRIdded Binary (GRIB) version 2 (GRIBv2) format files found on the NOMADS website. Files are typically organized by numerical weather prediction (NWP) model, geographic region and forecast hour. Using a batch scripting language hosted on an AWS Windows Server (denoted by [5] in Figure 28), datasets are downloaded in their raw form at prescribed times based on the specific models' characteristics. A computer software program, called a decoder, has been written using the C# (C-Sharp) programming language to unpack and read the various downloaded GRIB files to extract the necessary sensible weather fields (e.g., ceiling height) from the models' forecast GRIBv2 files. The raw data is converted to geoJSON format (Figure 29) and stored as documents[34] in a non-relational MongoDB database. Depending on the specific dataset, each document represents the forecast at a specific point (latitude/longitude) in the application's domain. This batch process is repeated on a schedule consistent with the models' runtime characteristics. At each forecast cycle, the new models' forecast *replaces* the current set of documents in the MongoDB. Historical weather data will not be stored in this application.

[34] Records in MongoDB are referred to as documents.

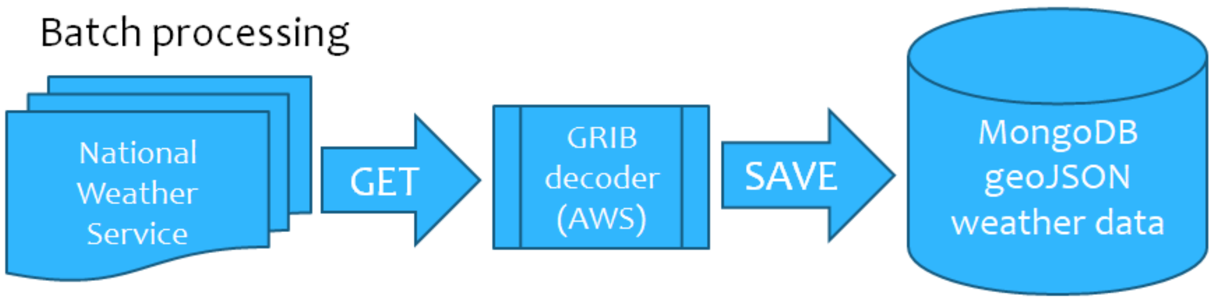

Figure 29. Data flow schematic of batch processing of datasets from the National Weather Service (NWS).

5.4.3 MongoDB database

The application developed for this research is highly data intensive with a total dataset size of ~25 Gb (Table 15). Given that this data is ephemeral, backup datasets are unnecessary. However, for real time redundancy and to provide high availability, the MongoDB is configured to contain three replica sets in a shared cluster that include a primary node and two secondary nodes. When the scheduled batch processing downloads the datasets from NOMADS (Figure 29) and converts them from GRIBv2 format, the resulting geoJSON documents are inserted[35] into the MongoDB's primary node. Each operation performed on the primary node also adds a record to an operations log, called an Oplog. Each secondary node reads the Oplog in real time and executes the same operation thus creating two replicated databases. In order to reduce the overall stress on the MongoDB primary node, the application reads in real time from one of the two secondary nodes. In the event of a failure of the primary or one of the two secondary nodes, the remaining nodes can be used to seamlessly provide the application with data and continue to store new documents as the automatic failover transition process is executed in the background.

[35] To optimize saving data to the MongoDB, documents are deleted before new data is inserted. This is necessary because an "update" is a significantly slower operation.

Table 15. Application dataset storage by dataset type required for primary MongoDB collections.

MongoDB collection	Size (Gb)
Current Icing Product (CIP)	0.18
Forecast Icing Product (FIP)	1.47
Graphical Turbulence Guidance (GTG) product	1.47
Global Forecast System (GFS)	9.39
National Blend of Models (NBM)	12.50
Miscellaneous (e.g., navigation database)	0.25
Total	**25.25**

5.4.4 Description of the application

The application is designed to run on both a desktop and laptop computer using an Internet web browser such as Google Chrome. It is also optimized to run as a progressive web app (PWA) on any computer including portable electronic devices. A PWA uses modern web APIs along with a traditional progressive enhancement strategy to create web applications across all major platforms. It provides several features that give the same user experience and advantages as native apps that can be downloaded from the App Store or Google Play. The web-based application consists of the following minimum features –

(1) Authenticate user id and password for sign in

(2) Display a route and overlay weather forecasts on an interactive map

(3) Accept and store user preferences and personal minimums

(4) Display weather forecasts along a route of flight to include clouds, airframe icing, turbulence, convective and precipitation potential.

5.3.4.1 Route definition

This is an application to help pilots minimize their exposure to adverse weather and is not intended to provide full navigation and routing capabilities that may be available through a full-featured Electronic Flight Bag (EFB) application such as Garmin Pilot. The database does contain most U.S. VFR and IFR waypoints, intersections, NAVAIDs and other fixes, but is not designed to accept complex routes that may include FAA-documented navigation routes such as victor airways, jet airways, Standard Instrument Departures (SIDs) or Standard Terminal Arrival Routes (STARs). However, routes can be manually defined (Figure 30) by entering a departure and destination airport using the airport's ICAO identifier. An optional route of flight may also be entered. These are flyover waypoints that are located between the departure and destination airports[36]. They can include any combination of airports, NAVAIDs, intersections and other fixes.

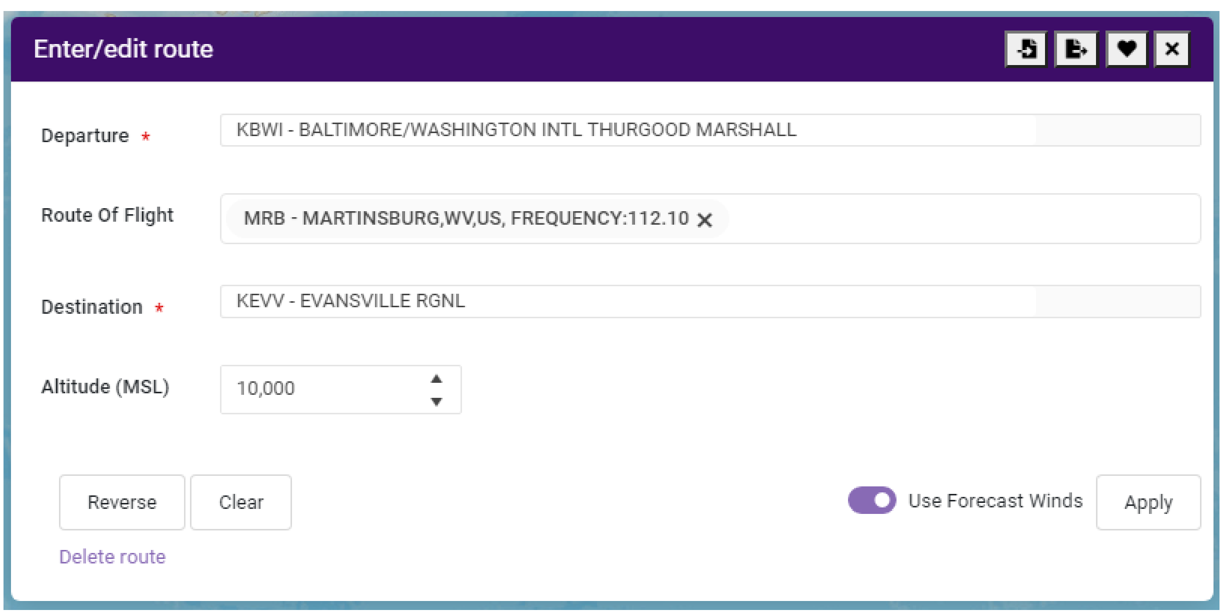

Figure 30. Route editor depicting a route originating at Baltimore/Washington International Airport (KBWI) with a landing at Evansville Regional Airport (KEVV) while flying over the Martinsburg, W.Va. NAVAID at 10,000 ft MSL.

[36] At this time there are no limits as to how many intermediate waypoints that can be entered.

In addition to the basic route, a cruise altitude must be identified. This allows the application to evaluate the pilot's exposure to airframe icing and turbulence along the proposed route at the altitude chosen. Once a route is defined, it is stored in the user's account record and displayed (Figure 31) on the interactive map as a great circle route.

5.3.4.2 Interactive map

Integral to any weather planning application is the ability to plot the latest weather reports and forecasts relative to a great circle route on an interactive map. While there are dozens of web-based libraries available, Leaflet[37] was chosen since it provides a very lightweight API and includes all of the features needed for this research. Leaflet is an open-source JavaScript library designed to allow developers to plot data on both desktop and mobile-friendly interactive maps.

Figure 31. Topographic base map showing a great circle route (gray) plotted from Baltimore/Washington International Airport (KBWI) to Evansville Regional Airport (KEVV) via the Martinsburg, W.Va. NAVAID waypoint.

The interactive map consists of a tiled open-sourced map with multiple weather layers. The user can choose from one of four base maps (Figure 32) to include two that offer

[37] See https://leafletjs.com/.

topographic features and a dark mode base map that allows the highest contrast and is also useful in the cockpit at night[38]. Topographical maps provide situational awareness when planning a route over rugged terrain. Weather in mountainous areas can be more challenging due to the effect terrain has on the wind in canyons or valleys. Clouds, precipitation and reduced visibility can obstruct or obscure the view of mountain tops and contribute to CFIT accidents. As weather layers are added to a topographic map, this provides substantial help to identify adverse weather in relation to mountainous terrain. None of these maps are certified by the FAA for air navigation; they are strictly for reference only during preflight planning.

Figure 32. Map base layer options to include two topographic maps, street map and a dark mode.

The application features six weather layers (Figure 33) that can be overlaid onto the map. There are three types of layers: (1) observational data such as pilot weather reports (PIREPs), surface observations (METARs) and a ground-based radar mosaic; (2) official advisories such as SIGMETs, G-AIRMETs and CWAs; and (3) forecasts such those from the NBM. While all of

[38] For a night flight pilots are encouraged to keep displays dimmed so the eyes can adjust to the darkness. A dark map minimizes the amount of ambient light in the cockpit.

these layers included in the application are important in making operational decisions, the forecast station markers layer is the primary focus of this research and the other layers will not be specifically addressed herein.

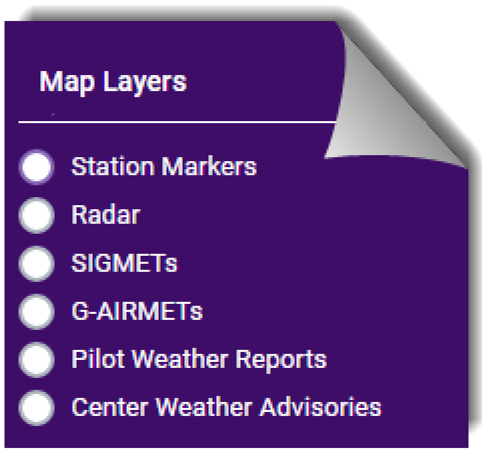

Figure 33. Map layer selector in collapsed view.

Airports are typically used as observation stations and also provide a location for aviation forecasts. The application provides access to both surface observations (METARs) and the NBMv4.0 forecasts for many airports throughout the United States through a layer selector menu (Figure 34). The Station Marker layer includes ten attribute filters to include Use Personal Mins, Flight Category, Ceiling Height, Surface Visibility, Surface Wind Speed, Surface Wind Gust, Surface Temperature, Surface Dewpoint, Dewpoint Depression and Weather. These filters are valid for both observations (METARs) and forecasts. Only one Station Marker filter can be applied at any time. Some filters have additional attributes to further filter the Station Markers shown on the map. Each layer has a unique style marker or icon placed on the map at the station's location and provides access to several critical observed or forecast weather variables (Figure 35) that are used by pilots to make many operational decisions and reduce risk.

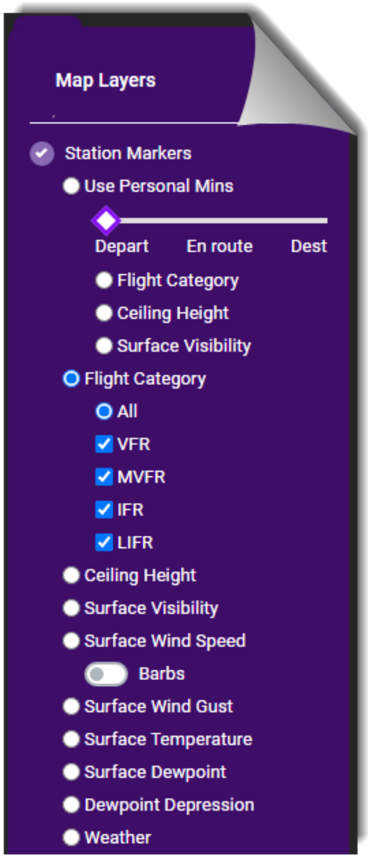

Figure 34. Station marker layer expanded view showing layer attributes with flight category attributes selected

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Figure 35. Each station marker provides essential weather information (observed or forecast) to include the valid time of the observation or forecast, ceiling height, cloud coverage, surface visibility, predominant weather, prevailing wind speed, prevailing wind direction, wind gust, surface temperature and surface dewpoint temperature.

Use Personal Mins – this provides the capability to evaluate the current or forecast weather at a station (airport) against a subset of personal minimums previously set. Three attributes are available to include flight category, ceiling height and surface visibility. Moreover, this can be applied to the personal minimums setting for the departure airport (Depart), en route airports (En route) or destination airport (Dest) accordingly. The result will be a solid-filled marker (Figure 36) using the traffic light concept outlined earlier[39].

Many long cross-country flights require one or more landings to refuel. This layer quickly identifies airports that are expected meet their personal minimum thresholds for ceiling height and surface visibility. Barring other adverse weather along the route, any green markers on the map identify airports that would be suitable landing sites to refuel with respect to ceiling and visibility at the time of arrival. Red markers, on the other hand, identify airports that are at or below their personal minimums and would create a high risk landing.

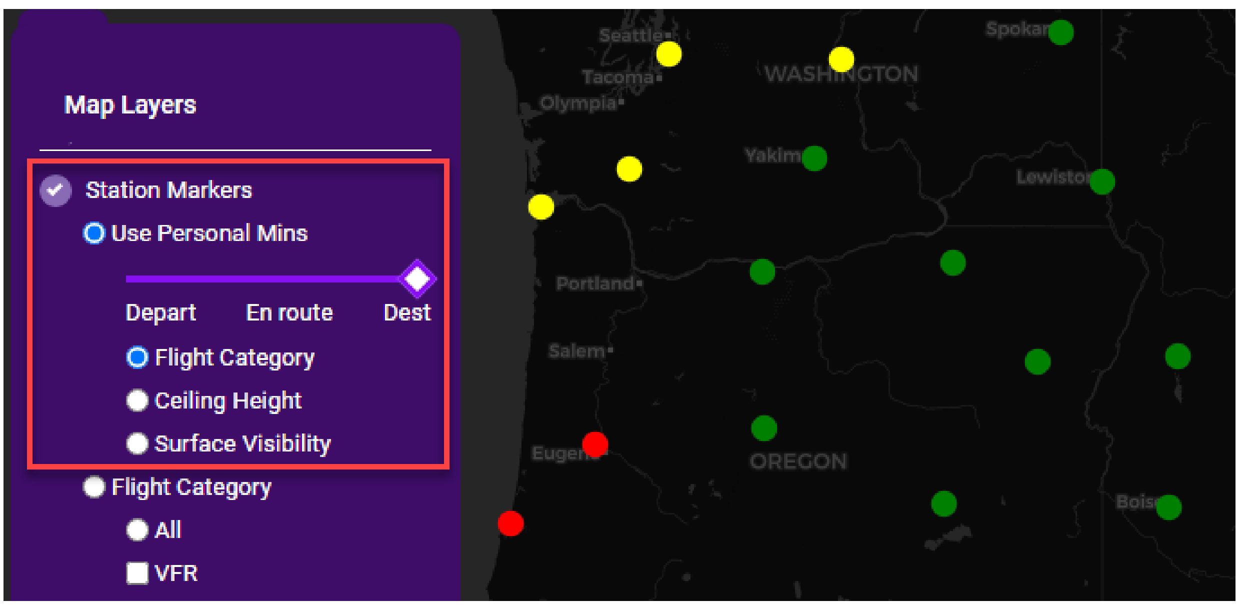

Figure 36. Station markers on the map are filtered to evaluate the personal minimums for the destination (Dest) flight category.

[39] Please note that the application of these personal minimums applies only for the time set on the departure advisor.

Flight Category – this provides the capability to filter the station markers on the map based on the current observation or NBMv4.0 forecast flight category. The flight category (Table 1) can be one of four values to include Low Instrument Flight Rules (LIFR), Instrument Flight Rules (IFR), Marginal Visual Flight Rules (MVFR) and Visual Flight Rules (VFR). The flight category combines both the ceiling height and surface visibility to produce a single categorical value.

The flight category marker is rendered on the map (Figure 37) as a filled (overcast), partially filled (scattered or broken) or unfilled (sky clear) colored circle depending on the observed or forecast sky coverage for the station and its categorical value for the time selected from the departure advisor. It can also be rendered as a colored square when the sky is cloud free below 12,000 feet AGL for the station[40]. When the sky is obscured for observations, indefinite ceilings are shown as a circular colored marker with an **X** in the center. The flight category layer can be further filtered by unchecking the various categorical attributes in the layer selector. For example, to only see stations reporting the "lowest" flight category (i.e., LIFR) the VFR, MVFR and IFR attribute filters need to be unchecked. This will filter out all station markers on the map except those with a magenta color.

When planning a cross-country flight, this layer quickly tells the pilot where ceiling heights and surface visibility are significantly reduced creating additional risk. For example, it would add significant risk for a pilot making a flight under VFR to plan a route through a widespread area with magenta (LIFR), red (IFR) or blue (MVFR) station markers. On the other hand, green (VFR) markers along the route of flight provide assurance that the ceiling height is greater than 3,000 feet and surface visibility is greater than 5 statute miles creating a lower risk. For pilots flying under IFR, low ceiling height and reduced visibility will indicate that an

[40] Automated observation systems cannot report cloud layers above 12,000 feet AGL.

instrument approach will be necessary. Even for experienced pilots flying IFR, a widespread area of magenta markers of LIFR conditions creates the potential for a challenging instrument approach and may require the flight to divert to an airport with a more favorable flight category.

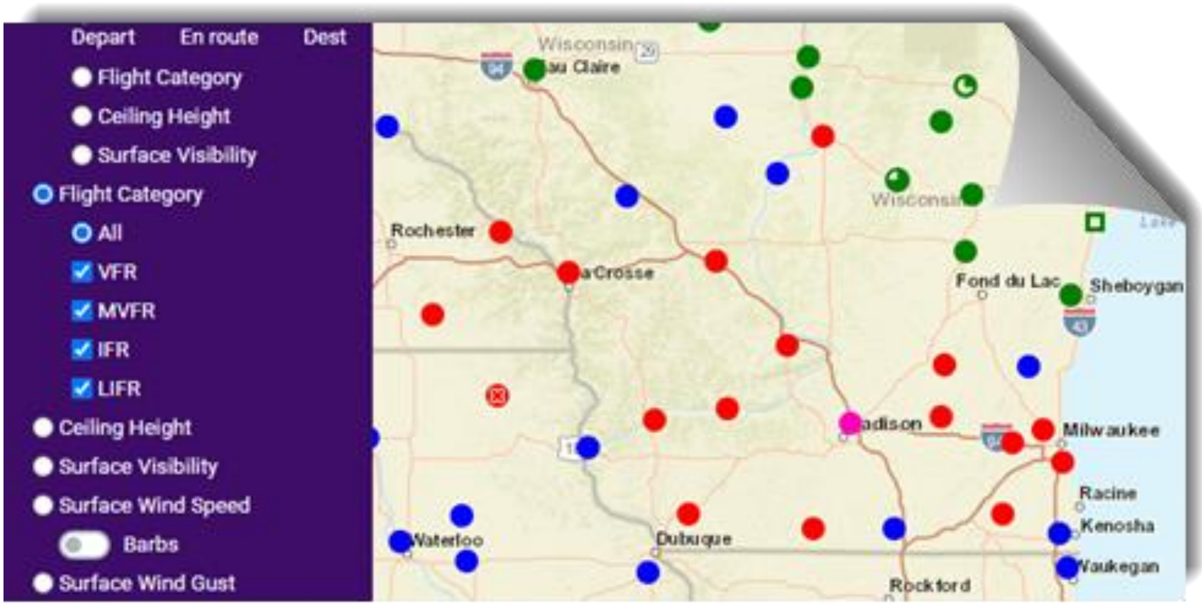

Figure 37. Flight category markers as displayed on the map for surface observations (METARs) for southern Wisconsin with all categorical attributes checked such that station markers for all four categories are shown.

Surface Wind Speed – this provides the capability to filter the station markers on the map (Figure 38) based on the current observation or NBM forecast prevailing surface wind speed forecast. This is shown on the map as a rounded-square marker can be displayed in knots or miles per hour depending on the user's preferences. A zero is shown for an observation or forecast of calm wind. The marker is color-coded[41] for the magnitude of the surface wind speed. Shades of green represent a prevailing wind speed of 10 knots or less. When the prevailing wind speed increases, warmer colors (yellow, orange or red) denote wind speeds in excess of 11 knots.

[41] Please note that the colors used for the prevailing wind and wind gust markers are not associated with the personal minimum colors of green, yellow and red.

Optionally, the prevailing surface wind can be displayed as traditional wind barbs (Figure 39) showing both the prevailing wind speed and wind direction.

Wind is responsible for the majority of aviation accidents, although they tend to be highly survivable. This layer creates the opportunity for the pilot to see airports forecast to have excessive wind speeds that may create a dangerous takeoff or landing. Flight planning to an area with a widespread area of strong surface winds may be indicative of low-level wind shear, thus, elevating the overall risk. Similarly, a strong surface crosswind can create an unstable approach that may lead to a runway excursion.

The surface wind barb marker can also assist the pilot to determine the magnitude of the crosswind component that might exist upon departure or arrival. Whether flying under IFR or VFR, crosswinds represent one of the most challenging tasks during a flight especially for pilots with little experience. For airports with multiple runways[42], this provides the necessary wind data to identify the runway that is most favorably aligned with the expected wind direction and reduces the risk of a wind-related accident.

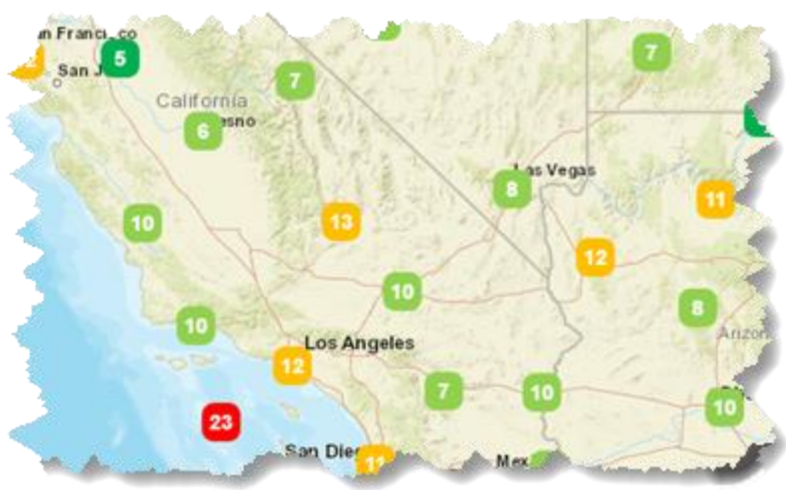

Figure 38. Prevailing surface wind markers (in knots) as displayed on the map for southern California depicting NBM forecasts at some departure time as set on the departure advisor.

[42] Even though an airport may have multiple runways, some are parallel runways or may not meet the required length or surface type (e.g., asphalt).

Figure 39. Prevailing surface wind barbs (wind speed and direction) as displayed on the map for southern California depicting NBM forecasts at some departure time as set on the departure advisor.

Surface Wind Gust – this provides the capability to filter the station markers on the map (Figure 40) based on the current observation or NBM forecast surface wind gust forecast. This is shown on the map as a rounded-square marker can be displayed in knots or miles per hour depending on the user's preferences. The marker is color-coded for the magnitude of the wind gust. Shades of green represent a wind gust at or below 20 knots. When the wind gust increases, warm colors such as yellow, orange or red denote wind gusts in excess of 10 knots. If a wind gust is not reported or forecast, the station's marker will be omitted for this layer.

This layer allows the pilot to assess the magnitude of the wind gust at the departure and destination airports. Even for the most experienced GA pilots, gusty surface winds can add a significant risk for takeoff or landing. Low-level wind shear events are often coupled with strong gusty surface winds which can lead to an unstable approach and hard landing with a propeller strike or runway excursion.

Figure 40. Surface wind gust markers (in knots) as displayed on the map for the Los Angeles area depicting NBM forecasts at some departure time as set on the departure advisor.

Weather – this provides the capability to filter the station markers on the map (Figure 41) based on the latest surface observation or NBM predominant weather and sky cover forecast. These markers are color-coded based on the flight category for that station. When windy or gusty conditions occur, a wind icon will be used as long as there is no other weather phenomenon to report (e.g., rain, snow, fog).

This layer provides the pilot not only with the forecast flight category similar to the flight category layer, but it provides the stations that are expected to see precipitation reaching the surface relative to the route of flight. Adverse weather nearby the proposed route such as low ceiling height, reduced visibility, strong surface winds, low-level wind shear, mountain obscuration, turbulence and airframe icing all tend to be found in and around areas of precipitation. Precipitation areas also signal a deeper and more organized weather system creating more complexity to safely navigate through the area. Most importantly, forecasts of ice pellets[43], freezing rain and freezing drizzle reaching the surface are especially dangerous for nearly all GA aircraft that are largely unprotected from this form of SLD.

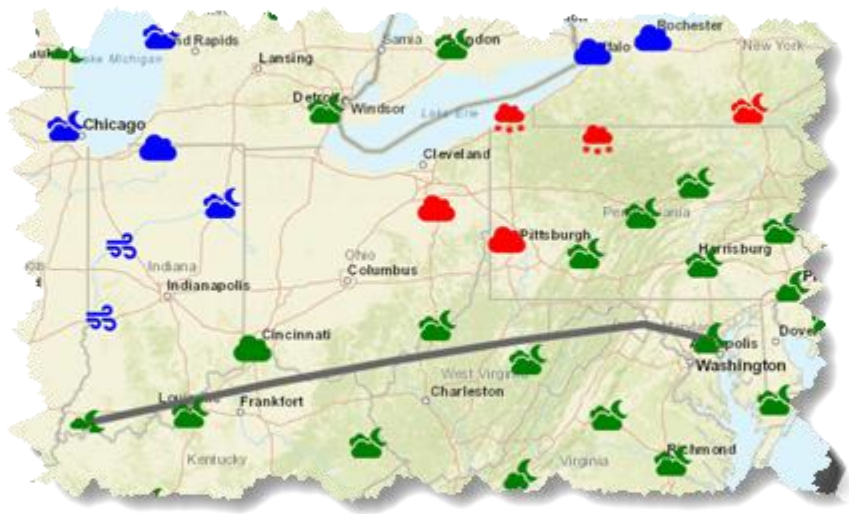

Figure 41. Predominant weather markers as displayed on the map for the Ohio Valley area depicting the NBM predominant weather forecast and sky coverage at the time set on the departure advisor.

5.3.4.3 Route profile

One of the more important features created for this research is the vertical depiction along the route called a profile view or vertical cross section. Such a route profile is an incredibly useful tool to integrate the forecasts to visualize how the weather will impact the pilot's proposed route of flight. This is especially critical for pilots flying under VFR as it defines the location and height of clouds and reduced visibility that may be encountered, especially in proximity to the surface. Before the route profile can be populated with forecasts, a route consisting of a departure airport, destination airport and optional flyover waypoints must be defined (Figure 30)

[43] While ice pellets do not create an icing hazard (they bounce off the airframe), it is known that they are a clear indicator of dangerous airframe icing aloft as snow is melted into a rain drop with a slushy core creating an SLD hazard.

using the route editor. The route profile (Figure 42) is comprised of the main viewport area, segment forecast points, optional flyover waypoints, proximity airports and time and distance information along the route. The proposed route of flight and Zulu time are presented at the top of the route profile.

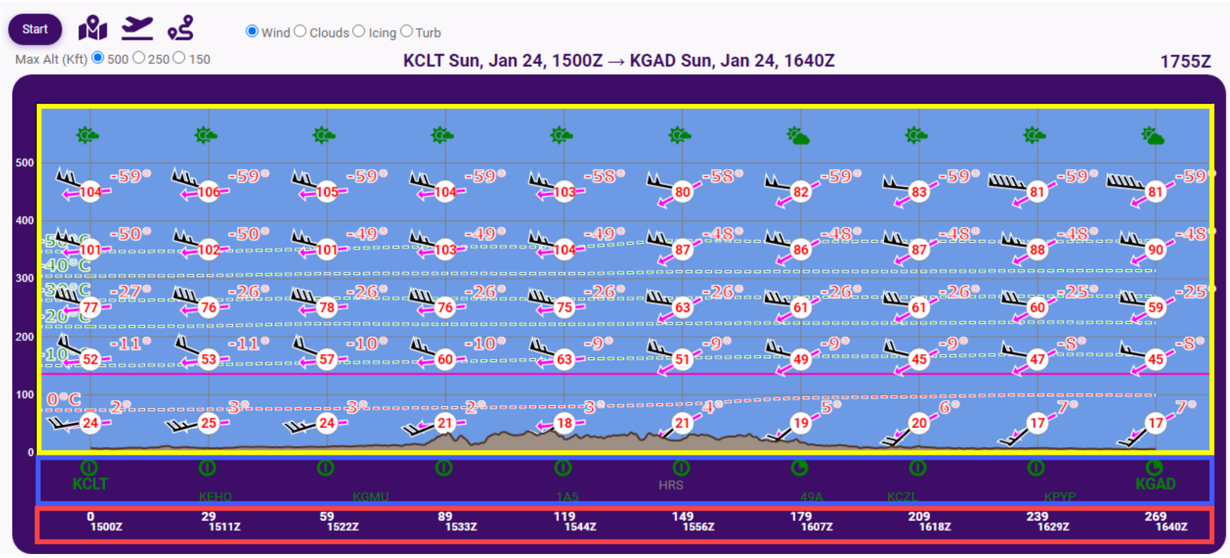

Figure 42. Route profile consists of the main viewport (yellow rectangle), flyover waypoints, segment forecast points and proximity airports (blue rectangle) and time and distance information along the route (red rectangle).

Altitude on the vertical profile (Figure 43) is shown on the y-axis in hundreds of feet above MSL. At the bottom of the profile, the route of flight is shown immediately below the main viewport and along the x-axis. The departure airport is always shown on the left and the destination airport is always shown on the right. Therefore, time and distance always increase from left to right. Optional flyover waypoints entered into the route of flight are depicted at their respective location(s) along the route and shown in gray.

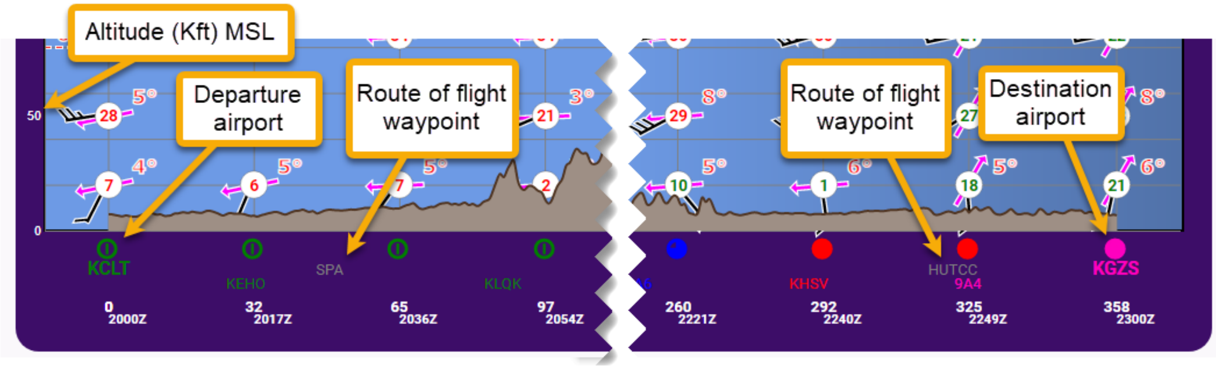

Figure 43. The bottom section of the route profile along the x-axis shows the departure (left) and destination (right) airports as well as the optional flyover waypoints for the route of flight. Altitude is shown in hundreds of feet MSL on the y-axis.

The main viewport is divided into two or more equidistant segments (Figure 44) for a route longer than 25 nautical miles. The length of the route will determine the number of segments. Shorter routes will have fewer segments. Routes over 1000 nautical miles[44] will have at most 14 segments. Each segment's start and endpoint becomes the location where data is rendered on the profile based on the forecast that is valid at the estimated time of arrival at that point. Weather forecast data (e.g., wind, icing, turbulence, clouds) is stacked vertically at these equidistant forecast points throughout the proposed route. This time-distance-altitude visualization offers a clear depiction of how the weather changes or deteriorates as the flight progresses along the proposed route relative to the performance of the aircraft used. This includes the possibility of airframe icing, turbulence, low ceiling heights and IMC.

[44] It is very uncommon for GA pilots to fly a single leg of a cross-country flight longer than 1,000 nm.

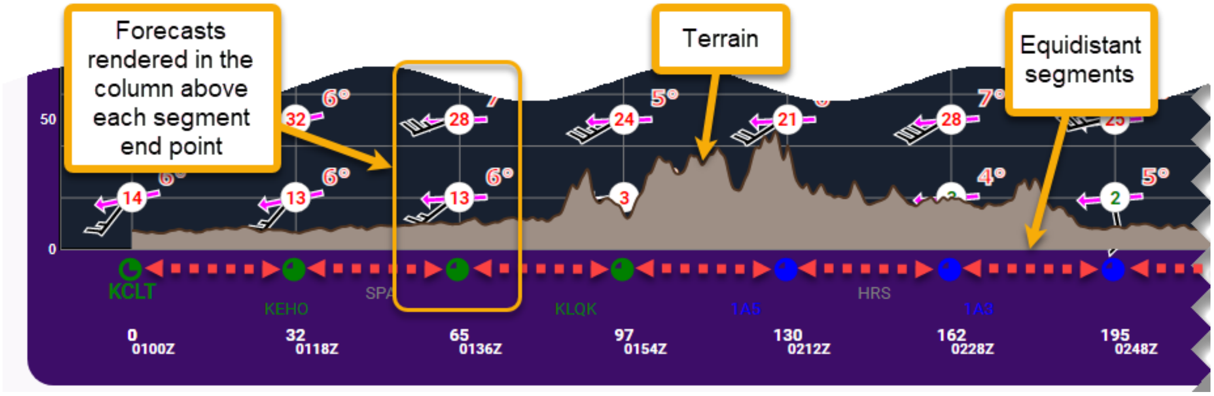

Figure 44. The route is divided into multiple equidistant segments with the end point of each segment representing locations (columns) along the route where forecasts are rendered.

Terrain along the route is shown in light brown profile (Figure 44) at the bottom of the main viewport. The terrain depicted in the application does not account for any other obstructions such as radio towers or moored balloons that may extend higher and should not be used for air navigation. Terrain is displayed as the highest precedence over other weather data or reference lines shown on the route profile so it will visually stand out. A route over mountainous terrain can be more difficult to negotiate when adverse weather is forecast. Planning a flight over rugged terrain increases the risk since it demands more attention and can contribute to additional complexity when choosing the proper altitude.

The elapsed distance and estimated time of arrival at each segment point (Figure 45) is shown below the route of flight. The estimated time of arrival is always relative to the time set on the departure advisor. The arrival time for each segment is calculated using the true airspeed provided by the user in the aircraft settings. This will factor in the headwind/tailwind component to determine the resulting ground speed along the route if the Use Forecast Winds toggle was set in the route editor.

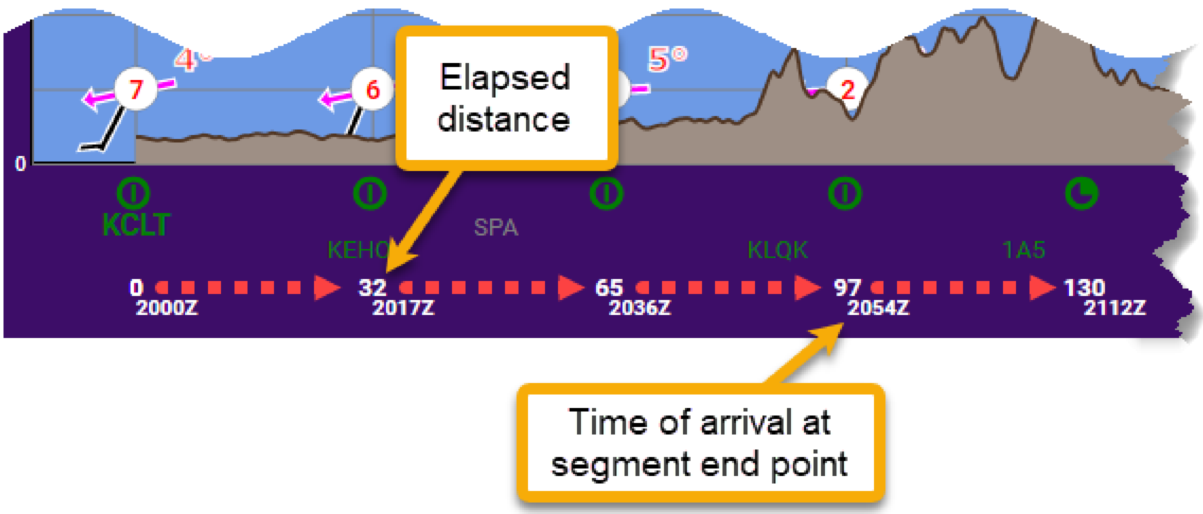

Figure 45. The last line at the bottom of the route profile shows the elapsed distance along the route of flight and the time of arrival based on the calculated ground speed of the flight.

Since time is a critical aspect of this research, it is represented as clearly as possible within the application. The time of arrival at each segment end point along the route is shown in white at the bottom of the route profile (Figure 45) and is depicted using the 24-hour clock or Zulu (UTC) time depending on the preferences set by the user. Regardless of the time preference set, a capability is provided to view the arrival time in both Zulu and local time at each segment end point (local time in this case is displayed using the 12-hour clock). Moreover, if any of the segment end points are located outside of the user's local time zone (Figure 46), the time in both zones are listed in the tabular view to avoid confusion.

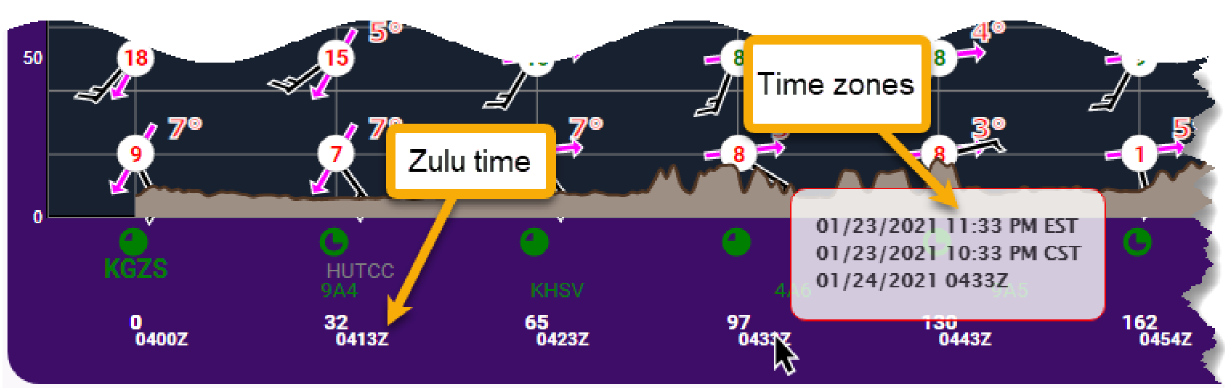

Figure 46. Time on the route profile is shown in a tabular view for both local (device) time and Zulu (UTC) time depending on the user's preference setting.

Survey respondents indicated that flying during daylight hours (versus nighttime) was very important. Consequently, to help distinguish between night and day the route profile's viewport background color (Figure 47) will be either light blue (for daytime) or black (for nighttime). During times of dusk and dawn the light blue will be shown to fade from blue into black and black into blue, respectively. The only exception is the icing profile view that will show a white background for all times of the day. This is to avoid a conflict with the icing severity forecast which also uses a similar shade of blue that is familiar to pilots.

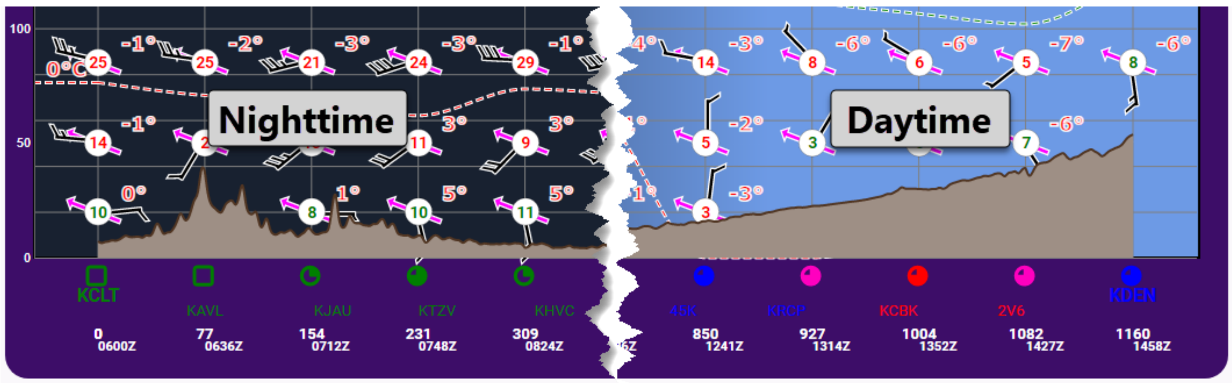

Figure 47. The use of a background color helps to distinguish between nighttime (left) and daytime (right).

When a route is defined, the application also requires that a cruise altitude be chosen. This is depicted on each route profile (Figure 48) using a solid magenta line. This is especially useful as a quick reference for flight through areas of clouds, airframe icing and turbulence aloft. Consequently, the calculation of ground speed from the pilot's planned true airspeed (and optionally factoring in the winds aloft) assumes that the flight originates at the en route altitude.

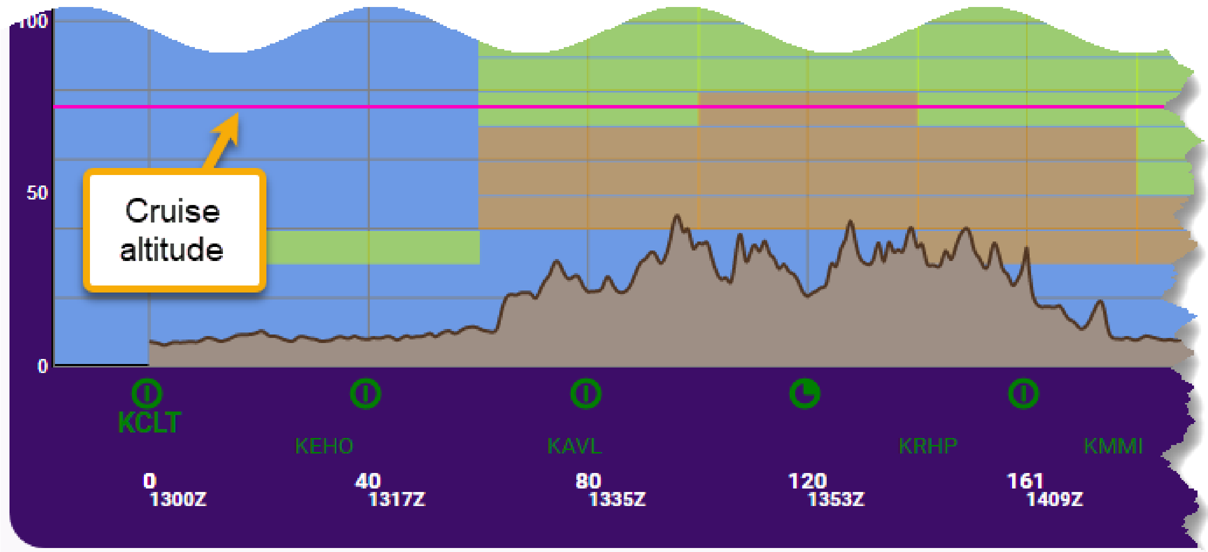

Figure 48. The cruise altitude is depicted by a magenta line as shown on the turbulence route profile. This is also displayed on the wind, icing and clouds route profile views.

Immediately below the route profile viewport a row of station markers are provided. These are located at the start and endpoint of each segment for the entire route. The first point on the far left represents the NBMv4.0 forecast for the departure airport and the last point on the far right represent NBMv4.0 forecast for the destination airport. Intermediate markers are not at airports but present the forecast conditions along the route at the surface. These define the weather conditions within 3 nautical miles[45] of the route based on the NBMv4.0 forecast. The color of these markers defines the flight category (Table 1) based on the forecast ceiling height and surface visibility. Sky coverage is also depicted graphically. A square marker identifies a clear sky condition and circular markers (Table 12) define a categorical sky cover with few, scattered, broken or overcast. A tabular view (Figure 49) of the forecast is available for each location along the route that includes the valid time, clouds, surface visibility, surface wind speed and wind direction (or calm winds), wind gust (if any), surface temperature and surface dewpoint. When a ceiling exists, clouds can also include a lower scattered cloud layer as well

[45] The FAA defines that a Federal airway as one that is within 4 statute miles of the route of flight. See https://www.faa.gov/air_traffic/publications/atpubs/pham_html/chap20_section_3.html.

from the NBM4.0 lowest cloud base (LCB). These color-coded markers give the pilot adequate warning about the potential for VFR into IMC conditions along the route.

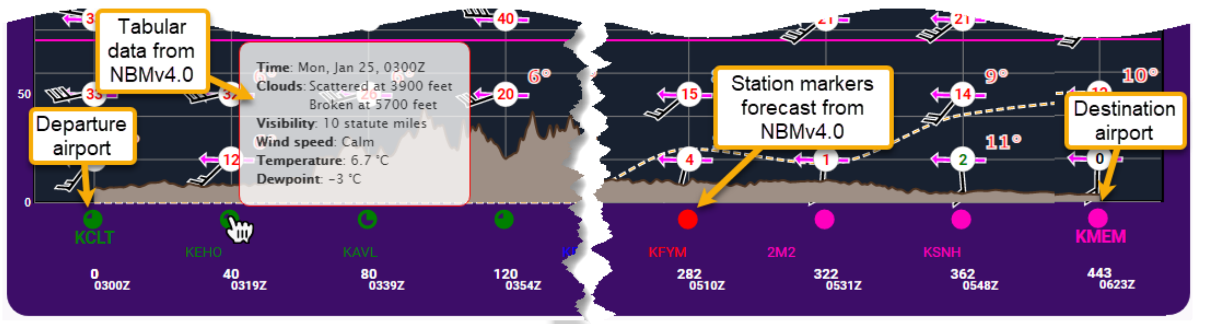

Figure 49. Forecast points along the proposed route are depicted by circular markers located at the equidistant segment end points depict the NBMv4.0 forecast. This includes a tabular forecast and forecast for flight category.

At the top of the profile view is a row of icons (Figure 50) that depict the NBMv4.0 predominant weather field and sky cover at the segment end points along the route of flight. Also available is a tabular presentation with the valid time of the forecast along with a plain English text translation. Icons are colored based on the forecast flight category. Moreover, these depict precipitation occurrence which helps pilots to highlight events which are often accompanied by adverse weather such as showers, thunderstorms, and freezing rain that often produces airframe icing, turbulence and low-level wind shear.

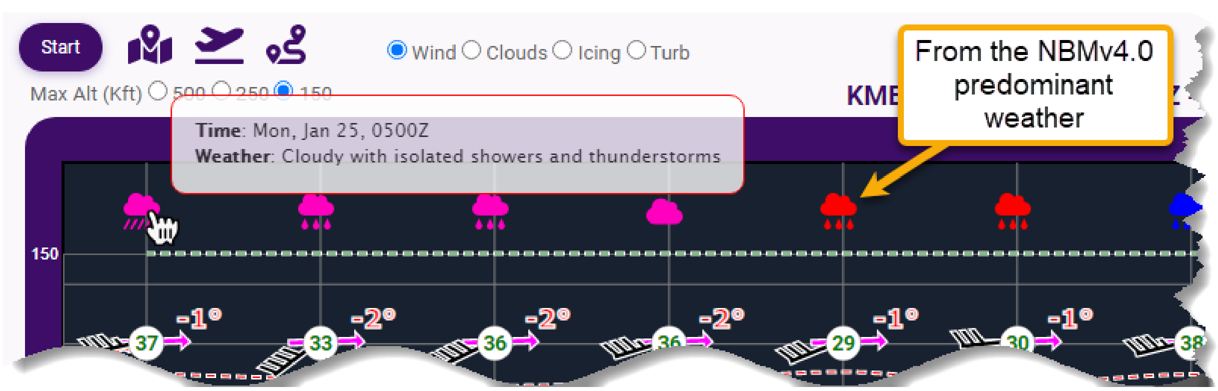

Figure 50. Icons presented across the top of the route profile at the forecast points are generated from the NBMv4.0 predominant weather field and sky coverage.

The route profile is split into four possible views (Figure 51). This includes a view for winds, clouds, icing and turbulence. These four views are mutually exclusive. Given that many GA aircraft have a regulatory service ceiling[46] and to increase the fidelity of the route profile, each view can be filtered to limit the maximum altitude displayed to include 500 kft, 250 kft and 150 kft MSL. Pilots flying under VFR would most likely want to use the latter view since it will provide the most detail in relation to the terrain profile. Some light fixed-wing GA aircraft have a pressurized cabin and will fly at an altitude above 25,000 feet MSL where clear air turbulence from the jet stream can be severe. Even so, a higher maximum altitude (e.g., 500 kft) is used to depict the overall depth of the clouds, airframe icing and turbulence. Deeper clouds, icing and turbulence are often the result of a more robust and potentially dangerous weather system.

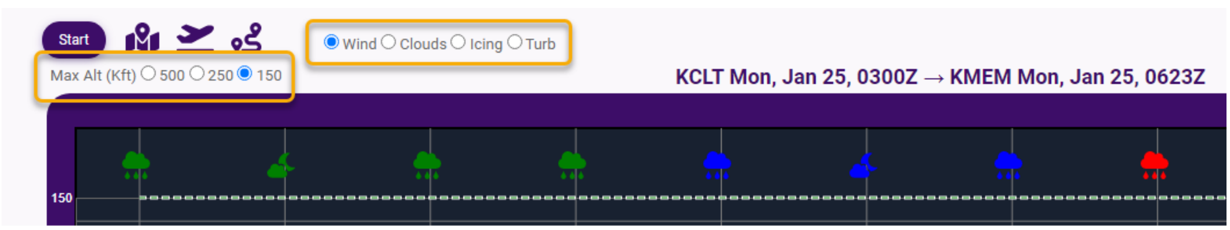

Figure 51. Four views are available to include Wind (default), Clouds, Icing and Turb (turbulence). The route profile can be filtered to a maximum display height of 50,000 feet (500), 25,000 feet (250) and 15,000 feet (150) above MSL.

Winds – this vertical profile provides the forecast upper-level wind speed, wind direction and temperature from the surface to 45,000 feet MSL based on guidance from the GFS model. At each segment start or endpoint along the route, a circle marker (Figure 52) will provide the forecast wind speed and direction using a standard wind barb shown in black.

[46] A service ceiling is defined by the FAA as the MSL height at which an aircraft with normal-rated load is unable to climb more than 100 feet per minute under standard atmospheric conditions.

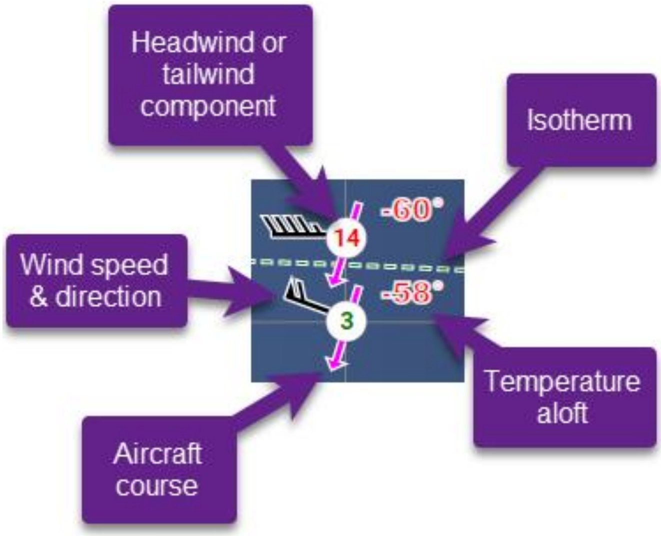

Figure 52. Markers on the wind profile depicting wind speed, wind direction, temperature and aircraft course relative to true north. The top wind barb is showing a wind direction from the west.

Additionally, each marker will also provide the GFS forecast temperature in degrees Fahrenheit or Celsius depending on the temperature preference set by the user. A magenta arrow is provided marking the course (heading) of the route at that location also in reference to true north. One ancillary goal for every pilot is to find the optimal altitude to minimize headwind or maximize tailwind. As a result, at the center of the white circle, the headwind/tailwind component is provided. A number in green indicates the magnitude of a *tailwind* in knots whereas a number in red indicates the magnitude of a *headwind* in knots. For a direct crosswind, a black 0 will be placed in the white circle. For light and variable or calm winds aloft, a black C will be shown with no wind barb present.

When winds are strong above the ridgeline in mountainous terrain, the risk for clear air and mountain wave turbulence exists especially when the wind direction is perpendicular to the mountain range. Airports that are located on the lee side of the ridgeline will typically be fraught with turbulence and low-level wind shear creating hazardous conditions during descent to land.

The Winds, Clouds and Icing profile highlights the temperature aloft using isotherms. These are depicted as colored dashed lines separated by 10°C intervals. Brown/tan dashed lines depict isotherms for a temperature aloft warmer than 0°C whereas green dashed lines depict isotherms for a temperature aloft colder than 0°C. And the 0°C isotherm (freezing level) is depicted (Figure 55) as a red dashed line. Most icing encounters occur when the static air temperature is at or between 0°C and -20°C when visible moisture is present. This allows the pilot to quickly determine the altitude that minimizes their exposure to airframe icing.

Clouds – this vertical profile contains a depiction of cloud cover and isotherms (Figure 53) along the route of flight. Clouds are depicted as rectangles showing the height and thickness of the expected cloud layers. White rectangles show cloud layers that are broken or overcast. A light gray rectangle represents few or scattered layer of clouds. For flights under VFR, this creates a clear indication of the potential for deteriorating weather en route and at the destination airport. Broken or overcast cloud decks close to the surface will significantly increase the risk of a VFR into IMC hazard.

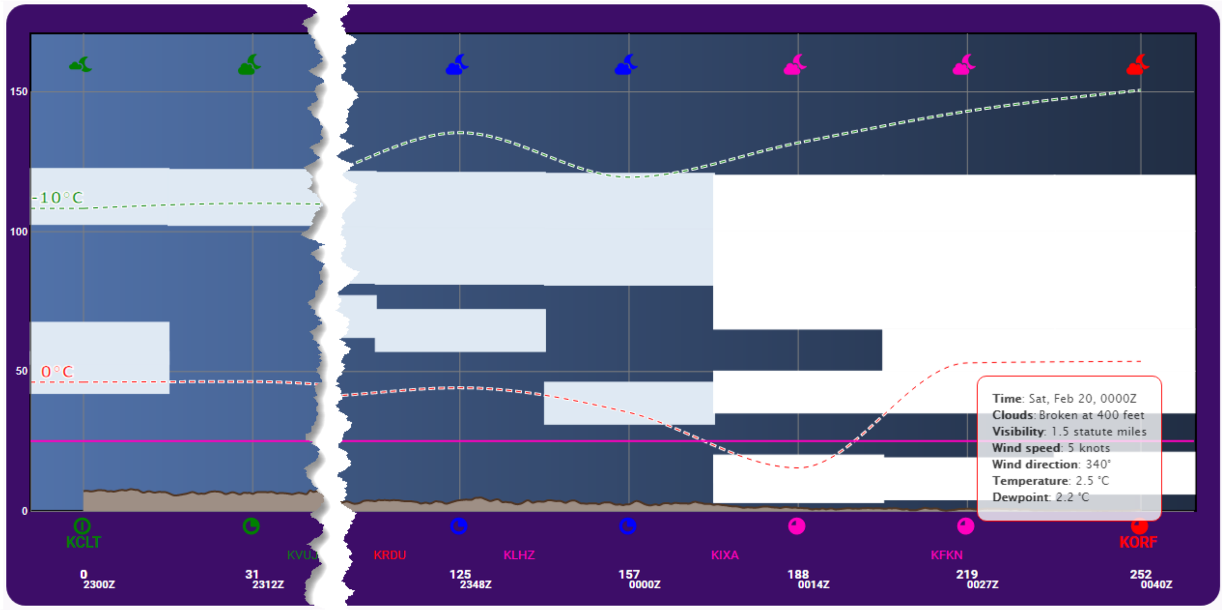

Figure 53. Clouds depiction on route profile using a route departing Charlotte Douglas International Airport (KCLT) to Norfolk International Airport (KORF) at 2,500 feet MSL. Conditions clearly depict deteriorating weather approaching the destination airport (right) with a 2300 UTC departure (left).

Icing – this vertical profile depicts the threat of airframe icing (Figure 54) along the proposed route of flight. This includes the icing probability, icing severity and supercooled large drop (SLD) potential from FIP. Forecasts for airframe icing are currently limited to 30,000 feet MSL and below with a lead time of 18 hours or less.

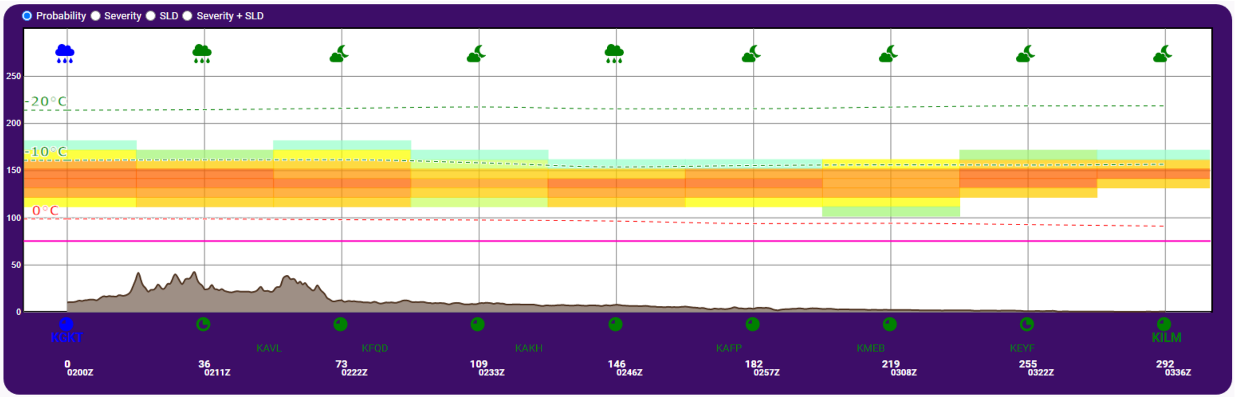

Figure 54. This is the airframe icing calibrated probability field from FIP. This is one of four icing depictions available to also include icing severity, SLD and Severity + SLD. This shows a direct route from Gatlinburg-Pigeon Forge Airport (KGKT) to Wilmington International Airport (KILM) at an altitude of 8,000 feet MSL. This altitude defined by the magenta line keeps the flight below icing conditions from 10,000 feet to 17,000 feet MSL.

Icing probability is depicted graphically (Figure 55) as a percentage from 10% to 85%. Colors are assigned to percentage ranges (e.g., 10% to 20%, 20% to 30%, etc.). Cooler colors such as blue and green depict lower probabilities whereas warmer colors such as yellow, orange and red depict higher probabilities. Any icing probabilities that are less than 10% are not shown. Flight at an altitude through any region depicting a 10% or greater probability will increase the risk of an encounter with airframe icing. The higher the icing percentage, the more likely the pilot will encounter airframe icing. This allows the pilot to choose an altitude that minimizes their exposure to icing conditions.

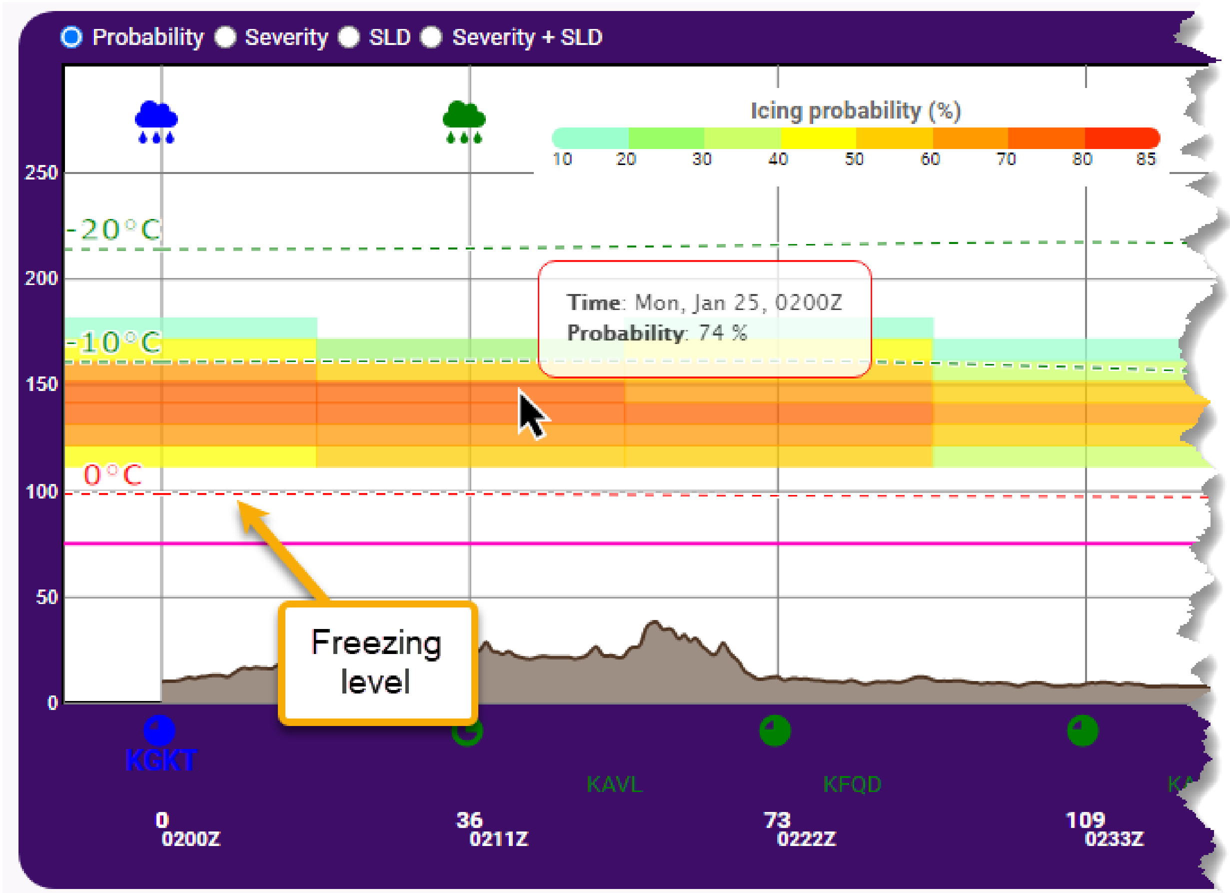

Figure 55. The calibrated icing probability route profile and the lowest freezing level as a dashed red line with the icing probability legend.

Icing severity provides a forecast for severity (intensity) of icing using a categorical forecast. Intensities include trace, light, moderate and heavy. Heavy is used instead of severe given that severe is reserved for how the aircraft reacts to the meteorological conditions, not the meteorological conditions themselves. Icing severity is presented in the icing profile viewport (Figure 56) as shades of blue with lighter shades of blue depicting lower intensity and darker shades of blue depicting higher intensity. The most serious encounters with airframe icing occur with intensities of moderate or greater where icing can build on the airframe that may be untenable for most small fixed-wing aircraft. Even aircraft with a certified ice protection system (IPS) should avoid areas of heavy icing that may overwhelm the system.

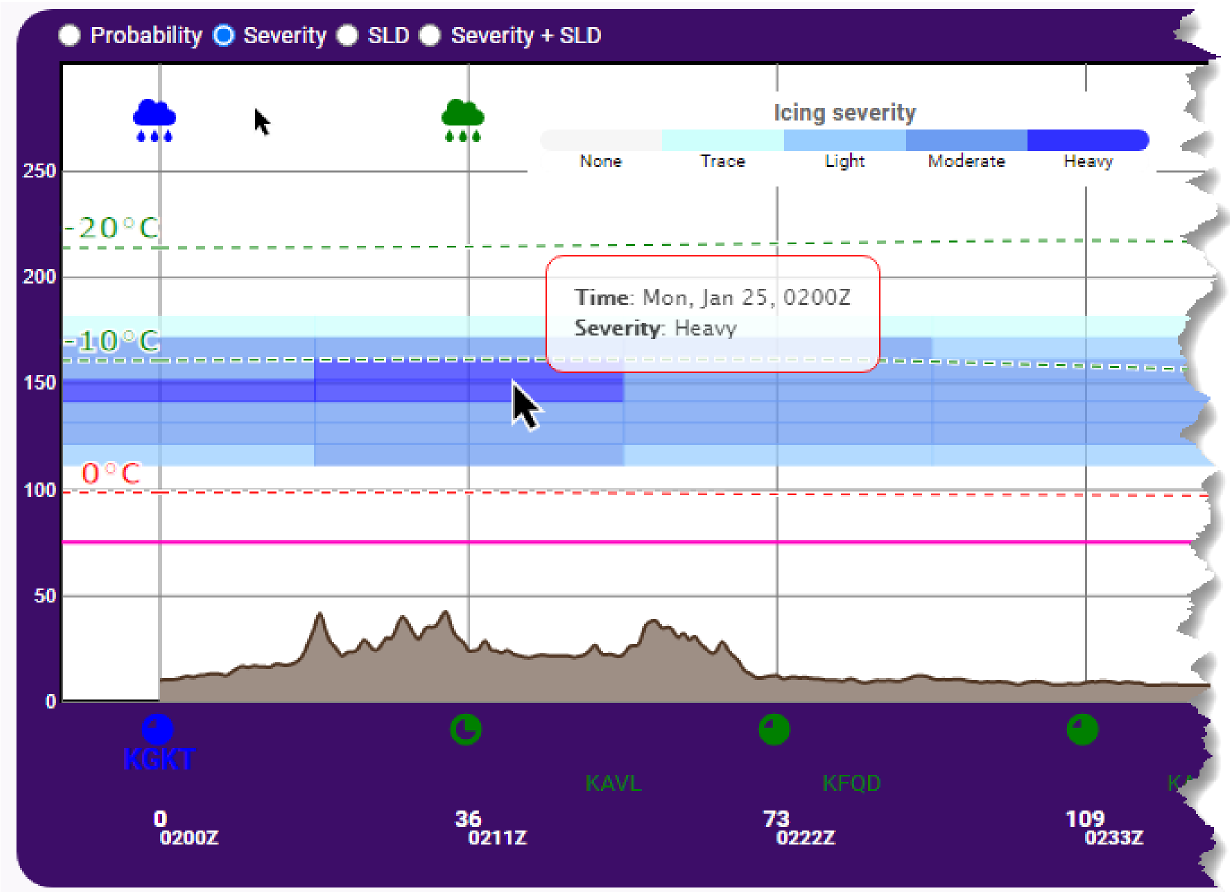

Figure 56. The icing severity field on the route profile with the icing severity legend. Heavy icing is shown at an altitude of 15,000 feet MSL just prior to reaching the Asheville Regional Airport (KAVL).

Supercooled large drop (SLD) icing is depicted graphically (Figure 57) as a percentage from 10% to 100%. Colors are assigned to percentage ranges (e.g., 10% to 20%, 20% to 30%, etc.). Similar to icing probability, cooler colors such as blue and green depict a lower likelihood whereas warmer colors such as yellow, orange and red depict a higher likelihood. Any SLD forecasts that are less than 10% are not shown.

Given that no aircraft is certified to fly into an SLD environment[47], flight through a forecast area of SLD is very high risk. Typically a forecast for SLD is accompanied by moderate

[47] Large turbofan aircraft (e.g., Boeing 737) are not certified for flight into SLD. However, they currently operate under an FAA waiver that permits flight into SLD conditions.

or greater icing due to the nature of typical icing signatures. As such, the application also provides a display that shows the SLD field overlaid onto the icing severity field (not shown).

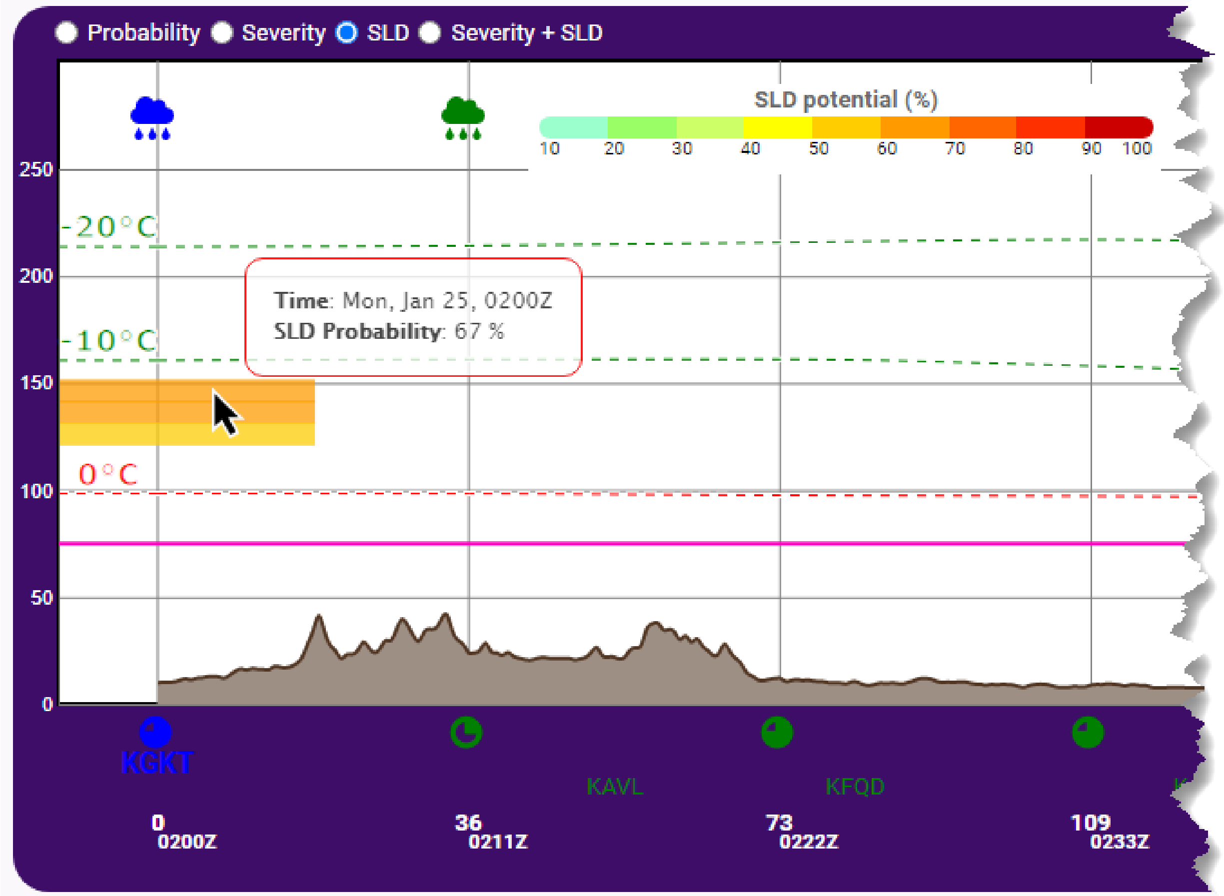

Figure 57. Supercooled Large Drop (SLD) potential field route profile and the SLD legend.

Turbulence – this vertical profile depicts (Figure 58) the threat of both convective and non-convective turbulence along the proposed route of flight from the GTG product. This includes clear air turbulence, mountain wave turbulence and a forecast that combines the clear air and mountain wave turbulence. Forecasts for turbulence are currently limited to 45,000 feet MSL and below with a lead time of 18 hours or less.

As mentioned earlier, turbulence used in this research is forecast as an eddy dissipation rate (EDR). The EDR is aircraft-independent and is an objective and universal measure of turbulence that is based on the rate at which energy is seen to dissipate within the atmosphere

(Sharman & Pearson, 2017). In other words, it is a measure of the turbulent state of the atmosphere at any particular time and location. When the EDR is large, the atmosphere is dissipating energy quickly and atmospheric turbulence levels are high. The amount of bumpiness felt in the aircraft also depends largely on the weight of the aircraft.

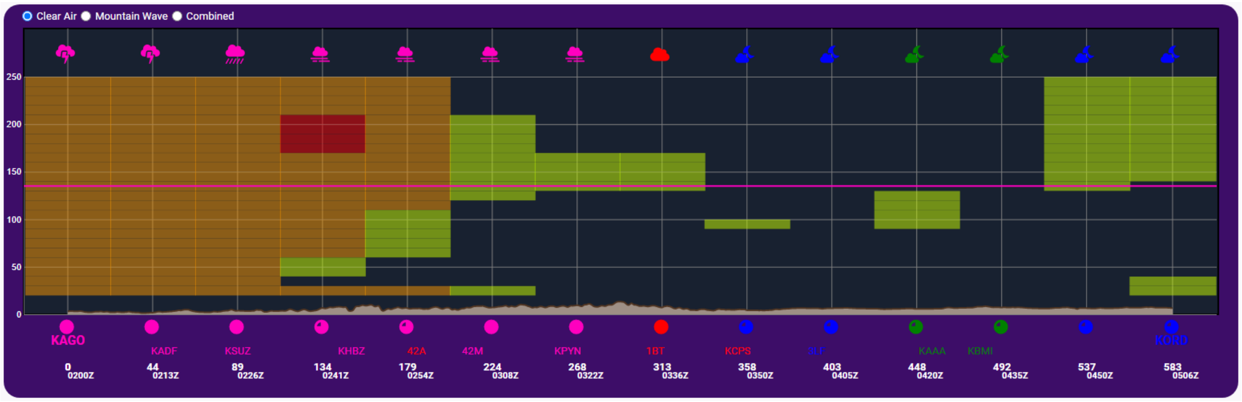

Figure 58. This is the clear air turbulence EDR turbulence field from the GTG forecast product. This is one of three turbulence depictions available to also include mountain wave turbulence and a view that combines both mountain wave and clear air turbulence.

EDR has a range from 0.0 to 1.0 in units of m^2/s^3. Therefore, the higher the EDR value, the higher the intensity of turbulence. Typically, EDR varies from near 0, defined as "smooth", to approaching 1, defined as "extreme" for most aircraft types. Note that in this research EDR values are multiplied by 100 to make it easier to interpret. Therefore, the turbulence values will range from 0 to 100, accordingly.

Most pilots are aware that the aircraft's maneuvering speed is higher when the aircraft is heavier. Moreover, heavier aircraft (Boeing 787) will experience the same EDR value of turbulence differently than a lighter aircraft (Cessna 172). Therefore, the maximum takeoff weight (Table 9) is used to define the EDR that is applicable.

Colors as listed below are assigned to the various categorical turbulence categories based on the aircraft weight class above and as selected the user's preferences.

Green – light turbulence;

Brown – moderate turbulence;

Red – severe turbulence;

Dark red – extreme turbulence.

The clear air turbulence selection depicts turbulence (Figure 59) that occurs outside of the cloud boundary. Most clear air turbulence occurs in the jet stream at altitudes above 15,000 feet MSL. It will also occur in the planetary boundary layer and is often referred to as thermal turbulence. Most high-level clear air turbulence tends to be more rhythmic in nature whereas low level clear air turbulence tends to have a more random bumpiness.

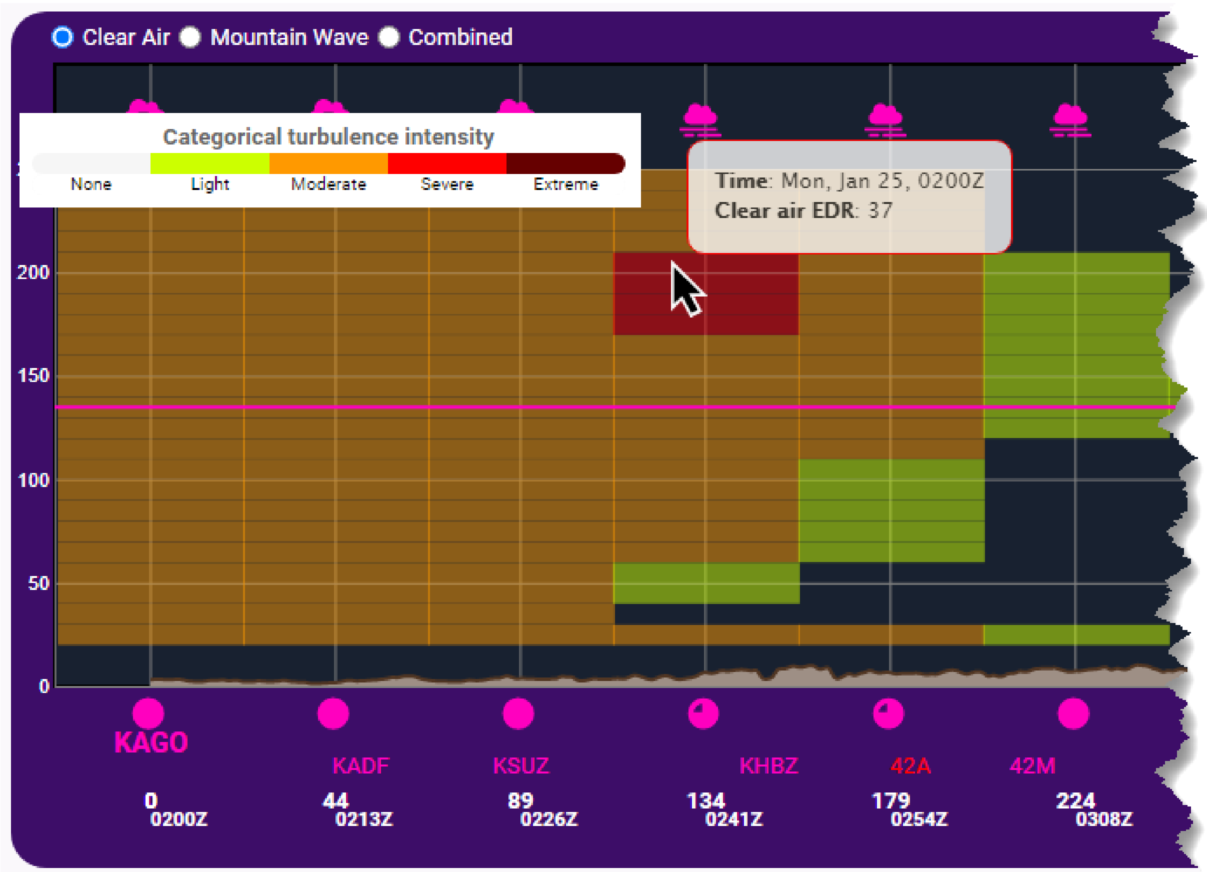

Figure 59. Route profile for clear air turbulence with the categorical turbulence intensity legend.

The mountain wave turbulence selection depicts turbulence that occurs solely as a result of gravity-induced mountain wave activity as forecast by the GTG product. Keep in mind that some mountain wave activity will be laminar and may not produce eddies that cause rapid acceleration or deceleration that is felt in flight. Instead, there still may be an up and downwash in non-turbulent lee waves not predicted by this forecast. The combined selection provides a depiction that includes both the gravity-induced mountain wave turbulence along with the clear air turbulence.

5.5 Summary of results

Of the ~7000 pilots that were emailed a survey for this research, a total of 1,123 pilots filled out the online questionnaire. Along with the collection of demographic data (e.g., certificate held, flight time, aircraft equipage, etc.) from the pilots surveyed this one-time survey was utilized to better understand the level of risk pilots were willing to assume based on key drivers of weather-related aviation accidents, especially those related to VFR into IMC (e.g., low ceiling height and reduced visibility). All responses were compiled and analyzed accordingly to demonstrate the respondents' areas of concern as it relates to minimizing exposure to adverse weather.

From this analysis, twelve personal minimum categories were selected and subdivided into three groups that included those that support the departure, en route and arrival phase of flight. Using a traffic light approach, each personal minimum category (e.g., surface visibility along the route) defined requires two settings representing the highest risk (red) and the lowest risk (green) with moderate risk (yellow) falling in between. The pilot must specify the green and red settings for each of these categories based on their own assessment of personal risk for a particular proposed flight. The application uses these settings to evaluate them against weather along the route and displays the results in a graphical display called the departure advisor.

The application developed for this research consists of a batch processing component to download and decode compressed digital weather forecasts on a specific schedule and application software designed to store personal minimum category values and settings, plot and store routes, evaluate the personal minimum thresholds against the weather forecasts along the route and display the weather in relation to the route to increase situational awareness. Weather datasets selected for this application include digital forecast from the GFS, NBM, FIP and GTG.

CHAPTER 6: DISCUSSION AND FURTHER STUDY

General aviation pilots flying light fixed-wing aircraft and helicopters are technically challenged in an effort to develop a plan that minimizes their exposure to adverse weather for an upcoming cross-country flight. This is, in part, the result of the way general aviation pilots consume pre-flight weather guidance and the inherent complexities and shortcomings in the current weather briefing process. This has led to weather-related fatal accidents, especially those associated with pilots flying VFR into IMC. A route-based automated application was developed through this research that simplifies and organizes weather guidance in a way that requires less technical interpretation and uses personal weather minimum thresholds and a time-leveraged evaluation to assess and quantify the personal flight risk. This is presented to the pilot in an intuitive color-coded system that is easy to interpret and is supported by other route-based visual weather displays, thereby reducing the probability of injury and fatality. The development of this decision-making tool has met the goals set out at the onset of this research.

Through the course of developing the tool outlined above, several unforeseen challenges arose that present themselves as exciting opportunities for future improvement. Since these aspects were not included in my original hypotheses and goals, they have not been formally incorporated into the current application. However, I have given each aspect considerable thought, and I have begun to explore how they might be incorporated in a future version of the application. These various aspects of each of these opportunities for improvement are outlined in the text to follow.

6.1 Route corridor

In the United States, a Federal airway includes the area within 4 statute miles on each side of the airway's center line. Pilots are expected to fly the center line of the airway while en route to their destination. However, navigation error permits the pilot to fly as much as 4 statute miles from the centerline. This airway definition was used as the route corridor for this research. Based on the grid spacing of the datasets used in this research (Table 16), a grid point will be reasonably close to the center line of the airway with the GFS forecast having the lowest overall resolution and the NBM retaining the highest resolution. In most cases, the nearest model grid point, as is used in this research, will be within this airway corridor.

Table 16. Grid spacing of datasets stored in the MongoDB and used by the application software.

Dataset	Grid spacing
Forecast Icing Product (FIP)	13 km (~8 statute miles)
Graphical Turbulence Guidance (GTG) product	13 km (~8 statute miles)
National Blend of Models (NBM)	2.5 km (~1.5 statute miles)
Global Forecast System (GFS)	0.25 degrees (~18 statute miles)

6.2.1 Linear interpolation

When the weather is fairly homogeneous on both sides of the route the current "nearest neighbor" methodology works quite well since any nearby grid point from the various datasets (e.g., turbulence) will result in a similar value. However, when the route is on a weather boundary or the weather is not homogeneous (e.g., widespread convection), what are appropriate methods to use to identify the underlying weather-related risks associated with the proposed flight? Is the nearest neighbor method the best approach? Or would some form of linear or spatial interpolation be more optimal?

The essential goal of any two-dimensional interpolation technique is to predict or estimate values of some continuous variable (e.g., model relative humidity) at unsampled points by using a linear combination of values at sampled points (Mei, 2014). A spatial interpolation process could be used to estimate the weather at these unsampled points along the pilot's proposed route. In a similar way, a proposed flight route consists of a departure and destination airport and optional flyover waypoints along a great circle route. It would be possible to take the model forecast and apply an algorithm to depict clouds, icing, or turbulence at various altitudes along the specific route. That would also extend to variables such as ceiling height or surface visibility.

One concern with such an approach is whether simple linear interpolation between two points will effectively represent the en route weather. A small timing error in the model forecast could produce a significant difference in the cloud cover encountered while en route, placing the pilot in a potentially dangerous situation. Another approach would be to extend this concept and evaluate the weather using a larger route corridor, perhaps even beyond the airway. A corridor defines some horizontal distance from the route whereby a more representative sampling of the potentially encountered weather can be captured while partially accounting for prediction errors inherent to all numerical model forecasts. Identification of an optimal corridor width would also be important.

6.2.2 Adaptive inverse distance weighting (IDW) approach

Would IDW provide a more optimal method for the interpolation of model output to the flight path? First, this two-dimensional method is straight-forward, works well with evenly-spaced data and does not require preprocessing (Mei, 2014). In other words, IDW does not require any known model or subjective assumptions such as selecting a particular semi-variogram model (Henley, 1981). Therefore, using any given set of random, regularly continuous variables (such as ceiling height and/or visibility on a two-dimensional map) the data-driven IDW approach is appropriate and could be easily automated.

One of the issues to consider for IDW is that it centers on how the distance inverse function relates to the definition of the neighboring radius. Therefore, IDW assumes that there is a relationship or similarity between neighboring points and the distance between those points (Setianto, A. & Triandini, 2013). Consequently, it is important to understand that weather can be extremely localized at times especially as it relates to ceiling (clouds) and visibility, but it can also be quite homogeneous over large regions. Moreover, proximity stations are often uniformly spaced about a proposed route and there would not be a need to correct for anisotropy.

Given these points, for localized weather events, IDW could provide a poor estimate along a pilot's proposed route. For example, a localized fog event forecast for a particular point that passes nearby the route could greatly influence many segments for that route. On the other hand, homogeneous weather, or nearly so, would likely yield a reasonable approximation similar to a linear interpolation. It is clear that with IDW each measured value has a local influence that will diminish with distance. Therefore, it seems the neighborhood size or radius of influence is an important variable to define, but this is outside the scope of this research project.

6.2 Altitude and the climb and descent profile

All flights consist of three phases, namely, climb, cruise and descent. During the climb and descent phase, there may be some exposure to airframe icing and turbulence depending on the altitude and forecast weather. However, this research only considers the cruise phase of flight and does not automatically factor in the hazards during the aircraft's climb and descent. In other words, it assumes that the flight starts and ends at the cruise altitude, which is not realistic but was less complex to implement. While omission of the climb and descent profiles constitutes a current limitation of this research, the limitation is less egregious than one might suspect.

Many GA flights are limited to 12,000 feet MSL and below primarily due to FAA requirements. That is, once the aircraft ascends to an altitude of 13,000 feet or higher, the pilot must carry and use supplemental oxygen. Also, many light GA aircraft have a service ceiling of 12,000 feet. It is expected, therefore, that many flights operate at an altitude that requires a limited climb and descent profile. For example, at a minimum climb rate of 500 feet per minute, it takes an aircraft 20 minutes to climb from sea level to 10,000 feet. With an approximate ground speed of 100 knots in the climb, the distance covered is 33 nautical miles. Segment lengths used in the application will vary depending on the length of the flight, but the climb profile to reach cruise altitude will typically occur just prior to reaching the first segment end point. A similar situation will occur on descent. The weather encountered during the climb and descent segments of each flight will thus be depicted in the vertical profiles provided for the starting location and the next one or two points. While exact flight path through those columns will not be explicitly evaluated for personal minimums, the pilot will not be completely left in the dark regarding adverse weather through that airspace. The airframe icing and turbulence threats will be visually represented in the vertical route profile for the climb and descent phases of flight.

In a future version of the application this limitation should be revisited to allow the user to save a climb and descent profile similar to the true airspeed at cruise currently captured. Once these parameters are known, the departure advisor will be able to evaluate where the flight will intersect forecast airframe icing and/or turbulence based on the user's personal minimums during the climb and descent phase of flight.

Furthermore, the departure advisor only evaluates airframe icing and turbulence based on the pilot's selected cruise altitude. For planning purposes, this is reasonable given that the flight plan filed with the FAA requires the PIC to include a single cruise altitude. However, in a future version of the application the departure advisor will evaluate a range of altitudes provided by the pilot to determine the most favorable altitude that minimizes the headwind component and the exposure to airframe icing and turbulence. The results of this evaluation will be an intuitive depiction of risk similar to the traffic light concept used in the current version of the departure advisor with an emphasis on altitude selection.

6.3 Alternate airport consideration

All pilots flying in controlled airspace must consider an alternate airport during preflight planning in the event a flight cannot be completed due to unexpected adverse weather. There are various reasons an alternate airport becomes necessary, however, one of the primary safety concerns is adverse weather that does not meet the pilot's personal minimums. In the event the weather is not as forecast at the destination or while en route, the ability to choose a much lower risk alternate airport is needed to reduce the overall risk. In other words, planning a conservative "Plan B" is essential to mitigating the overall risk of any flight.

This research has not directly addressed this part of the preflight planning. Indirectly, the map view is always an option to determine an acceptable alternate airport. The map can be filtered (Figure 60) to evaluate airports against the pilot's personal weather minimums for flight category, ceiling height or surface visibility. In this case, the map is filtered to show that a flight to Chester Catawba Regional Airport (KDCM), the personal weather minimum flight category for the destination airport evaluates to green. This means that the weather is expected to meet the pilot's personal minimums with a reasonable margin at the time of arrival. However, there are nearby airports to the north and east of KDCM that are red and indicate they do not meet the pilot's destination personal minimums for flight category and are not acceptable to use as an alternate airport in the event the actual weather ends up being worse than forecast at KDCM. This makes it is easy to see the airports along the route that may serve as appropriate alternates.

In a future version of the application it will integrate an "alternate minimums" category to address this issue as part of the departure advisor. In conjunction with using the map as outlined above, the pilot could select an optional alternate airport using the route editor and validate that airport's weather against the alternate minimums.

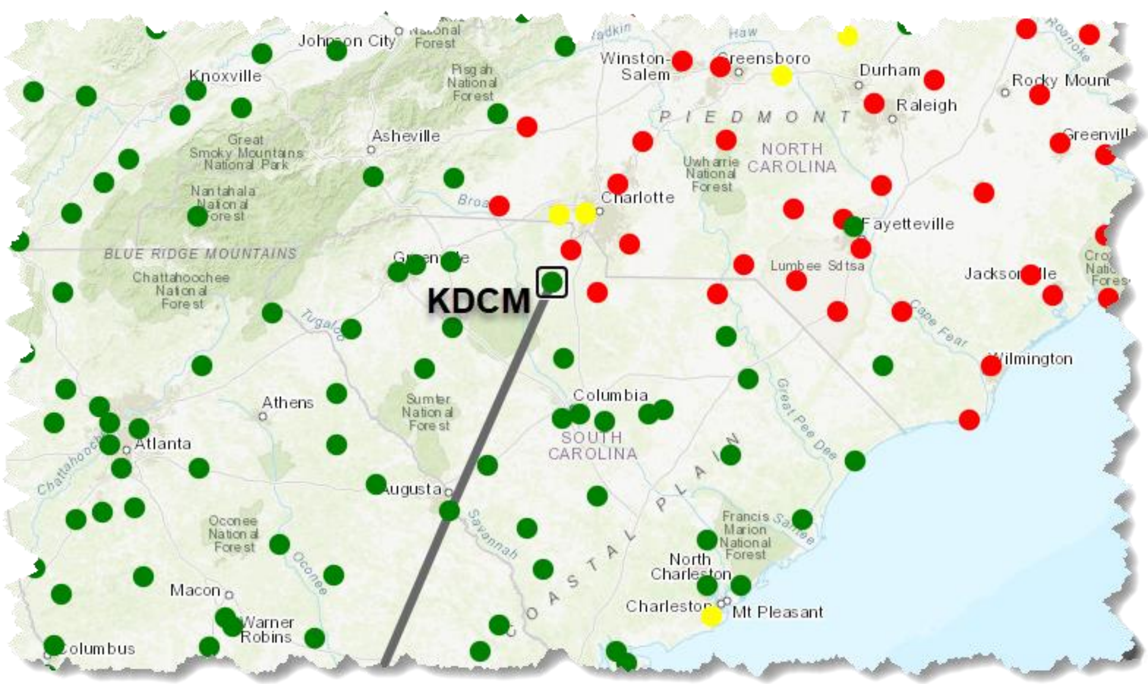

Figure 60. Demonstrates the map filtered to evaluate the forecast against the pilot's personal weather minimums at the destination airport using flight category for selection of an alternate airport.

6.4 Color-blindness considerations

Congenital color vision deficiency (CVD) or color-blindness affects 8% of men and fewer than 1% of women (Chan et al., 2014). Many people with CVD find it difficult to distinguish red from green or blue from orange.

In the United States, every GA pilot must undergo a physical exam by an aviation medical examiner (AME) every two or three years depending on the pilot's age. This includes a pseudoisochromatic color plate test. If the pilot fails the test, a limitation will be issued on their medical certificate that says, "Not valid for night flying or color signal control." In addition to the primary test performed by the AME, the pilot has the option of taking an operational color vision test that is administered by the FAA. A description of these tests can be found in FAA Order 8900.1, FSIMS, Volume 5, Chapter 8, Sections 5-1523.F, 5-1526.E.6, and 5-1527 F. For third-class medicals the test includes –

(a) A signal light test administered at an airport air traffic control tower; and

(b) A practical test in which you must read and correctly identify colors on aeronautical charts (FAA, 2014).

In the end, color blind pilots can be approved to fly with no restrictions assuming they pass the required tests.

There are dozens of aviation applications and EFBs available to pilots that display weather information that includes color. However, none of the major software applications provide settings to address the issue of color-blindness. Instead, they rely on the device (e.g., the iPhone) to provide well-tested accessibility options that allow color-blind pilots to use a common color filter for all applications on their device. Therefore, rather than developing color-blindness filters unique to this application, allowing color-blind users to select an optimal third-party filter would be the safest course of action.

6.5 Personal minimum thresholds for night flights and routes over mountainous terrain

Studies cited in this research have shown that flight within a DMA and during nighttime hours is known to add additional risk to any GA flight as it relates to weather. This is especially the case for pilots flying under VFR. Mountains can induce severe or extreme turbulence, can be obscured by clouds, precipitation and mist and localized effects of wind can create a challenging takeoff or landing in valleys and canyons. The application is designed such that a pilot can adjust their personal minimum thresholds when planning a flight within a DMA or at night. However, in a future version of the application pilots will specify an alternate set of personal minimum thresholds for nighttime and flight in mountainous terrain. Essentially, every personal weather minimum category will have a night and mountain threshold to allow for those different levels of personal risk. The departure advisor then applies those alternate minimums as necessary for routes or portions of a route that are conducted at night or intersect a DMA.

6.6 Global Ensemble Forecast System (GEFS)

In this research it was concluded that using the output from a single deterministic model (i.e., GFS) was more appropriate than using the results generated from an ensemble forecast such as the Global Ensemble Forecast System (GEFS). Furthermore, in addition to GEFS, NBMv4.0 already incorporates ensemble forecasts such as the Short Range Ensemble Forecast, Canadian Model of Client-Centered Enablement model and the Navy Global Environmental Model into the blend. There were three primary considerations for not using an ensemble forecast that includes (1) restricted temporal resolution of the ensemble output; (2) timeliness of the ensemble output; and (3) whether the ensemble output provides enough additional skill or pragmatic information to warrant its use for this application.

Ensemble forecasts, however, do offer distinct advantages over a single deterministic model forecast using a single set of initial conditions. An ensemble forecast is a collection of "member" forecasts that verify at the same time but were derived from slightly different (but equally viable) initial conditions. This is accomplished by repeatedly incorporating small random perturbations into the initial conditions of either a single model or different models to create an ensemble of forecasts. Once the ensemble forecast is complete, simple statistical analysis of the individual member forecasts provide an ensemble mean forecast (which is often superior to any individual forecast) and measures of forecast uncertainty (based on the spread among the ensemble members).

6.6.1 Temporal resolution

All of the primary weather datasets used by this application were streamlined using NOMADS. Currently, this site provides access to the GFS model forecasts at 1 h temporal resolution. The equivalent GEFS ensemble output (i.e., with a 0.25° horizontal resolution) is only provided at 3 h resolution. Therefore, use of the GEFS output would require interpolation to the native 1 h resolution and would undoubtedly miss critical aspects of rapidly evolving weather that could be captured by the GFS forecasts. Given that an overarching goal of this research was to provide pilots with increased situational awareness of hazardous weather, using lower resolution ensemble forecasts seems less helpful to pilots.

6.6.2 Timeliness

Given the later time slot on the NCEP supercomputers, the GEFS ensemble forecasts require an additional 2-3 hours to become available for download from the NOMADS site (as compared to the GFS deterministic run). On average, the GFS completes the 72 hour forecast products (Figure 6) at ~0950 UTC. Under most circumstances, the 0600 UTC dataset for the deterministic GFS is available for download on NOMADS shortly after 1000 UTC. In comparison, the corresponding 06 UTC dataset for the GEFS ensemble completes at ~1225 UTC (Figure 61) and the output is not available on NOMADS until after 1240 UTC. In this way, the GFS offers a much more competitive advantage over the GEFS.

EVENT	Average Start Time	Average End Time
ENS FORECASTS	09:22:04	12:22:44
ENS PRODUCTS	09:34:22	12:24:46

Figure 61. The average end time (UTC) of the 0600 UTC run of the Global Ensemble Forecast System (GEFS).

6.6.3 Skill and pragmatic use of ensemble forecasts

One of the more valuable aspects of the ensemble forecast is the variability about the mean. Knowing that a forecast has a higher uncertainty is an important and useful commodity for a meteorologist. The difficult challenge is how to quantify this for the typical GA pilot in a way that is both useful and easy to consume and fits within the scope of the application. Since pilots are not meteorologists and do not easily grasp these concepts, too much use of ensemble information may introduce "mixed messages" such that it becomes counter-productive and may not meet the goals of the research to improve GA safety.

Moreover, the ensemble mean usually has at least as much skill as an equal-resolution deterministic run. In fact, the ensemble mean can be more skillful than a higher-resolution deterministic run. This is especially true as the lead time of the forecast increases (Figure 62), especially beyond 3 days. Within that 0-3-day period, the difference in skill is minimal. The application developed for this research is designed to provide the pilot with guidance over a 2-3-day window, and therefore, cannot take full advantage of the additional skill at later lead times that an ensemble mean provides. Moreover, the period between two to six hours from the current time is the most critical for aviation operations (NWS, 2016; Ghirardelli & Glahn, 2011). While there may be some improvement using an ensemble mean for relative humidity (clouds), winds aloft and temperature, it is not significant enough to warrant losing the temporal resolution and the dataset freshness provided by the deterministic run.

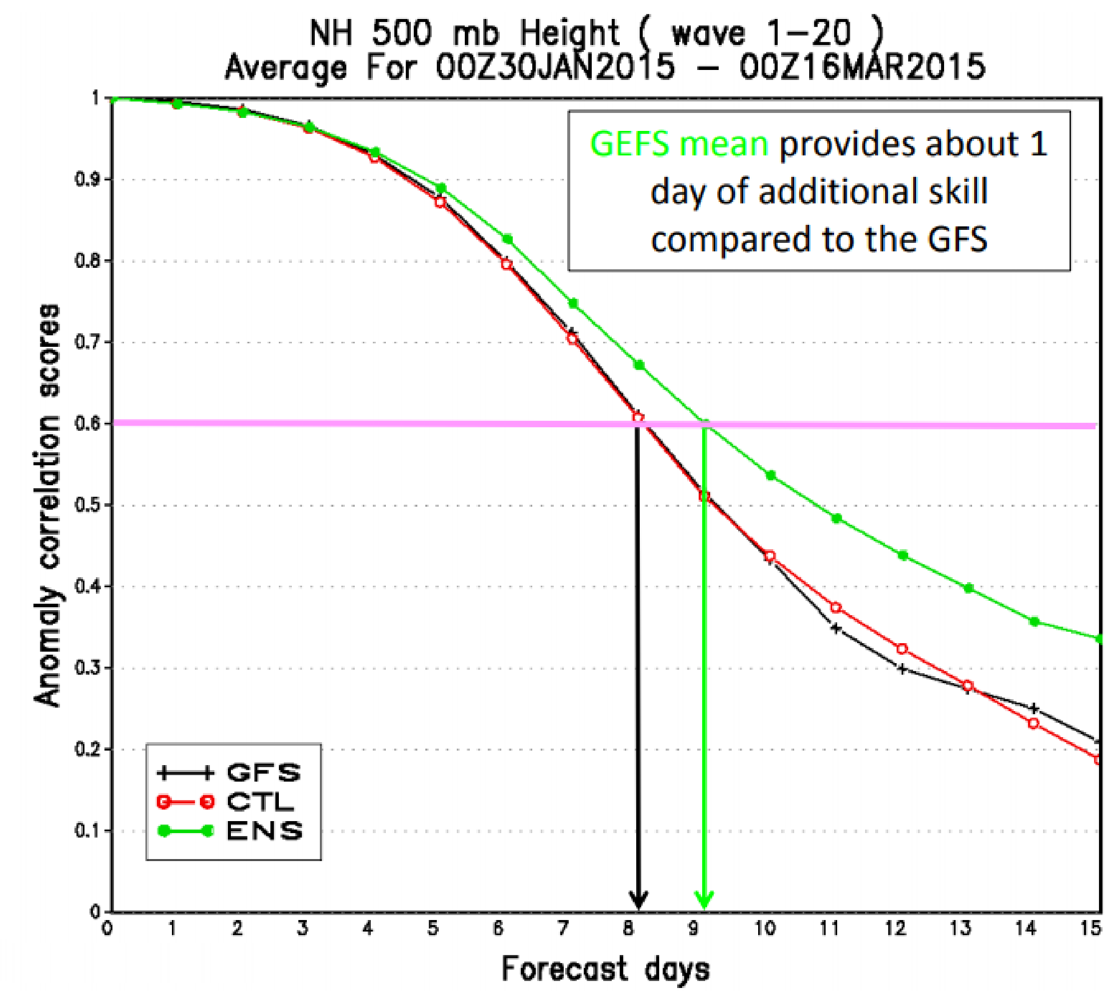

Figure 62. Anomaly correlation scores of the GFS versus the GEFS ensemble mean for the Northern Hemisphere 500 mb height from January 30 - March 16, 2015. Image courtesy of the NCEP Environmental Modeling Center (EMC).

6.7 Gender, race and geographic location of pilots

The questionnaire that was performed for this research did not capture the gender, race, socioeconomic status or geographical location of the pilot's surveyed. Currently the FAA does not collect statistics on the race of general aviation pilots. However, there is no doubt that these elements can make a difference in how pilots of different genders and those that fly in different locations may perceive risk differently. For example, a pilot who has spent most of their time flying in southern Florida may not fully understand the risk of airframe icing since the freezing levels are usually quite high most of the year in this area. Also, a pilot who has flown mostly in the Middle Mississippi Valley or Midwest may never have experienced the effect that mountains have on weather.

According to the FAA statistics published each year, 5.45% of certificated pilots in the United States are women[48]. It is well known that gender plays a significant role in the perception of risk. Men and women, in fact, perceive the same risks quite differently and they may perceive different risks or in some cases even associate different meanings to what appear to be "the same" risks (Gustafsod, 1998). For the purposes of this research it has been assumed that all pilots perceive risk in the same way, regardless of their gender, race or physical location. As such, the personal weather minimum categories chosen allow for those differences in risk perception. This includes pilots that may fly in and around mountainous areas where the perception of risk and actual risks are higher. Therefore, the pilot can decide how to assign that risk and what elements are more important and those that are not.

[48] See https://www.faa.gov/data_research/aviation_data_statistics/civil_airmen_statistics.

6.8 Conclusions

The primary goal of this research was to develop a targeted application that reduces weather-related GA accidents and fatalities, especially those associated with VFR into IMC. This was accomplished through a literature review of aviation accidents and pilot questionnaire of personal risk to develop an automated web-based decision-making tool for use by GA pilots making cross-country flights in light fixed-wing aircraft and helicopters. To minimize exposure to adverse weather, the application integrates high resolution digital weather forecasts and evaluates those against a pilot's personal weather minimums and provides the results in an easy-to-consume way while providing guidance to suggest the most appropriate time to depart.

This application will be promoted to GA pilots through contacts within several high-profile organizations to include AOPA, Experimental Aircraft Association (EAA) and SiriusXM Aviation Weather as well as various aircraft-type clubs and organizations focused on aviation safety such as the Cirrus Owners and Pilots Association (COPA). Additionally, announcements will be made through email campaigns, aviation discussion forums and through social media (e.g., YouTube, Twitter and Facebook) to promote the application to GA pilots throughout the United States.

This decision-making tool will have a robust support system to capture immediate feedback and other ideas and suggestions from its base of dedicated users. To build a complete picture, Google Analytics will be utilized in a secure way to gain a deeper insight of how the tool is being used and how pilots are engaging with the application. These leads and discussions with other pilots through social media outreach will create a community of pilots to enhance the application as it is being utilized daily. Additional features, including those discussed in this research, will be added to a future version of the tool to improve its intrinsic value to GA pilots.

As the U.S. Supreme Court noted[49] in 1980 "'safe' is not the equivalent of 'risk-free.'" General aviation is inherently risky. Furthermore, hope is not a plan. While this tool does not substitute for common sense and will not prevent an accident due to a jaunty disregard or lack of respect for safety, this tool will give every GA pilot a consistent method to quantify and reduce their risks and to minimize their exposure to adverse weather for each and every flight they are contemplating.

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[49] Indus. Union Dept. v. Amer. Petroleum Inst., 448 U.S. 607 (1980)

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APPENDIX : NOTICE OF IRB APPROVAL OF EXEMPTION

UNC CHARLOTTE

OFFICE OF RESEARCH COMPLIANCE
9201 University City Boulevard
319 Cameron Hall
Charlotte NC 28223-0001
(704)-687-1871
Web site: http://research.uncc.edu/
Federalwide Assurance (FWA) #00000649

To: Scott Dennstaedt
Geography and Earth Sciences

From: Office of Research Protections and Integrity

Date: 11/19/2020
RE: Notice of Approval of Exemption with No End Date
Exemption Category: 2.Survey, interview, public observation
Study #: 21-0171

Study Title: Email survey of general aviation pilots for dissertation research

This submission has been reviewed by the Office of Research Protections and Integrity (ORPI) and was determined to meet the Exempt category cited above under 45 CFR 46.104(d). This determination has no expiration or end date and is not subject to an annual continuing review. **However, you are required to obtain IRB approval for all changes to any aspect of this study before they can be implemented.**

Important Information :

1. Human Subjects Research (HSR) activities that can be conducted virtually/remotely should be conducted virtually/remotely. Protocol Modifications are required to adjust data collection procedures to remote data collection (e.g., phone, online or virtual).
2. The operational status of the research/study location where HSR activities will occur will guide whether the activities should occur.
3. Off-campus HSR activities may occur if the organization, institution, agency, business, etc. is operational and is willing to support the researcher to conduct the research.
    - Researchers will be representing the University and therefore, regardless of the organization's standards, researchers must adhere to University, local, and state requirements regarding the use of face coverings, physical distancing standards, group size limitations, etc.
4. Conducting HSR activities on-campus (Main campus, Center City campus, and other locations that may be extensions of the University) is subject to the operational status of the University.
    - Researchers must adhere to all University, local, and state public health and safety requirements including wearing face coverings whenever indoors and maintaining physical distancing.
    - Researchers must adhere to the Niner Nation Cares requirements including the 6 Ws (Wash, Wear, Wait, Wipe, Watch, and Wave) and limitations on the size of gatherings.
5. Should the operational status of off-campus study locations change, the University's operational status change, Mecklenburg County and/or the state of North Carolina impose higher restrictions (stay-at-home orders), researchers must comply with these requirements and therefore HSR activities, regardless of whether the activities are off-campus or on-campus may need to halt.

Study Description:

My dissertation research under Dr. Matthew Eastin will survey a group of ~10,000 general aviation pilots via an email questionnaire. Responses will not be made public and respondents may opt out at any time. I am hoping to learn more about how pilots view adverse weather limits as it relates to flight planning.

Your approved consent forms (if applicable) and other documents are available online at
http://uncc.myresearchonline.org/irb/index.cfm?event=home.dashboard.irbStudyManagement&irb_id=21-0171.

The Investigator Responsibilities listed below apply to this study. Carefully review the Investigator Responsibilities.

Investigator's Responsibilities:

The above-cited determination has no expiration or end date and is not subject to annual continuing review.

However, the Principal Investigator needs to comply with the following responsibilities:

1. Modifications **must** be submitted for review and approval before implementing the modification. This includes changes to study procedures, study materials, personnel, etc.
2. Data security procedures must follow procedures as approved in the protocol and in accordance with ITS Guidelines for Data Handling.
3. Promptly notify the IRB (uncc-irb@uncc.edu) of any adverse events or unanticipated risks to participants or others.
4. Complete the Closure eform via IRBIS once the study is complete.
5. Be aware that this study is now included in the Office of Research Protections and Integrity (ORPI) **Post-Approval Monitoring program** and may be selected for post-review monitoring at some point in the future.
6. Reply to ORPI post-review monitoring and administrative check-ins that will be conducted periodically to update ORPI as to the status of the study.
7. Three years (3) following this Exemption determination, ORPI will request a study status update (active/not active).

Please be aware that approval may still be required from other relevant authorities or "gatekeepers" (e.g., school principals, facility directors, custodians of records).