Pilots' Weather-related Decision Making: Results from a Workshop and a Survey

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Abstract

This research was aimed at providing information to support three major research efforts: [1] the global NGATS ATM Project, [2] a specific project associated with the enhancement of the Convective Weather Avoidance Model (CWAM), and [3] a research and development effort aimed at producing an advanced flight deck display that includes weather information. An information-gathering workshop was held, and survey data were collected. In both cases, the objective was to gain insight into the information used by pilots in making weather-related decisions and to understand some of the processes involved in making such decisions. Results from the workshop and the survey are described in this paper. In addition to yielding novel data, some of the data are consistent with the objective data collected by Rhoda and Pawlak (1999), who analyzed real-world traffic flows. The data are presented in a form that might serve to be fruitful as input into a model, such as CWAM, that attempts to predict pilots' decisions. Such data also could serve as guidance in determining the types of information that might appear on an advanced cockpit display that contains weather information.

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Context and Goals of Project

The current document summarizes two research efforts put forth by the Flight Deck Display Research Laboratory (FDDRL), a part of the Human Systems Integration Division (TH) at NASA Ames Research Center. Specifically, this document summarizes the methods and findings associated with a workshop and an online survey. In both cases, the objective was to gain insight into the information used by pilots in making weather-related decisions and to understand some of the processes involved in making such decisions.

Project as Part of the Overall NGATS ATM Project

Both the workshop and the survey were supported by the Next Generation Air Transportation System Air Traffic Management (NGATS ATM) Airspace Project and were meant to support the goals of the NGATS ATM project.

> The NGATS vision calls for a system-wide transformation leading to a new set of capabilities that will allow the system to respond to future needs of the Nation's air transportation. The list includes communication and physical infrastructure, the acceleration of automation and procedural changes based on 4-dimensional (4D) trajectory analyses to substantially increase capacity with safety and efficiency of the National Airspace System (NAS), and dynamic reconfiguration of airspace to be scalable to geographic and temporal demand … The JPDO outlined the needs of NGATS by specifying a vision and operating principles. Of major consideration in the principles is that the future Air Traffic Management (ATM) systems will consider user needs and performance capabilities, utilize trajectory-based operations, and optimally utilize human capabilities, automating, where appropriate, the functions performed by pilots and controllers. The NGATS vision calls for the human role within the system to move toward strategic decision making, and the tactical separation role moves towards full automation (Swenson, Barhydt, & Landis, 2006, pp. 1-2).

Swenson et al. (2006) go on to state that weather is "the biggest source of disturbance to the system" (p. 35). Therefore, in order to realize the Next Generation Air Transportation System, weather must be addressed in a comprehensive manner. When considering an advanced system, the uncertainties associated with weather obviously are problematic. Weather creates uncertainty in the environment because it is a dynamic variable in the world, but it also creates uncertainty because the humans in the system react to weather in a variable fashion. Numerous organizations are working toward improving our ability to interpret, visualize, and forecast weather in the environment (e.g., the National Oceanic and Atmospheric Administration, the University Corporation for Atmospheric Research, etc). The efforts described herein were meant to focus on weather-related uncertainties that arise in the NAS as a result of variability in *humans' responses* to weather.

In short, the workshop and survey efforts described herein were directed at achieving the overall goals of the NGATS ATM Project, with ***specific objectives*** to:

- provide information about pilot behavior in the presence of hazardous weather,
- suggest methods to quantify these behaviors, and
- determine the flight deck information that is used by pilots in their weather avoidance decision making.

Limitations were placed on the scope of, what would otherwise be, a tremendous undertaking. Specifically, the efforts discussed in this document were limited to an exploration of *Part 121* operations. For the most part, these efforts also placed considerable emphasis on pilot decision making in the presence of *convective* weather activity. However, certain portions of the research allowed for some insight regarding other types of weather phenomena, and these findings are discussed where appropriate.

Project as Part of the Efforts to Improve the Convective Weather Avoidance Model

Although the aforementioned objectives place emphasis on *pilots* within the NAS, these efforts are less limited in scope than might be implied from a simple review of the objectives. In addition to the broader goals of the NGATS ATM Project and the aforementioned objectives, the findings presented here are meant to have more immediate applications, and these applications are not limited to those that involve pilots. In particular, the results of these efforts are a part of a task within the NGATS ATM Project, in which efforts are being put forth to improve the Convective Weather Avoidance Model (CWAM).

CWAM was developed and is being refined by researchers at Massachusetts Institute of Technology (MIT), Lincoln Laboratory (DeLaura & Evans, 2006) and is meant to predict convective regions around which pilots are likely to deviate. Developers of the model refer to these regions as "weather avoidance fields," and they are working to refine the model such that it might be used in *air traffic management* (that is, to assist those "on the ground"). Specifically, CWAM is being developed to estimate the impact of weather on the NAS, from the perspective of air traffic management.

A model that effectively predicts convective regions around which pilots will deviate would neither underestimate nor overestimate the impact of weather on the NAS. Underestimating the area of weather avoidance fields would yield an underestimation of weather's impact on the NAS. In such a case, pilots actually would use less airspace than had been predicted, which might yield delays that had not been foreseen. CWAM developers (DeLaura & Evans, 2006) need not err on the side of overestimating the weather avoidance fields either, as would be the case if the model was intended for use by pilots making real-time, tactical judgments. Overestimating the area of weather avoidance fields would yield an overestimation of weather's impact on the NAS. In such a case, pilots actually would use more airspace than had been predicted, which would result in an inefficient air traffic management plan. CWAM developers hope their model will be able to enhance both the safety *and* efficiency of the increasingly crowded NAS.

In order to predict the circumstances under which pilots will deviate due to convective weather, CWAM (DeLaura & Evans, 2006) obviously must contain and access relevant information. Identifying the relevant information needed in order to make such predictions might, in theory, appear simple. Specifically, some might argue that CWAM developers need only to refer to the Federal Aviation Administration (FAA) Aeronautical Information Manual, which provides a specific suggestion to pilots. The manual states that pilots should avoid thunderstorms characterized by "intense radar echo" in en route airspace by at least 20 nautical miles (40 km). At first glance, one might hypothesize that, with the inclusion of this guidance, the model might approach optimal predictive power. However, empirical data challenges the notion that pilots consistently adhere to the aforementioned FAA guidance (e.g., Rhoda & Pawlak, 1999), and these findings have been confirmed more recently with a general aviation pilot population as well (Beringer & Ball, 2004). If pilots are not consistently adhering to this rule, a model based solely on the FAA's guidance would not perform optimally. In fact, as described in the following paragraphs, Rhoda and Pawlak's research (1999) suggests that a model based solely on the FAA's guidance to pilots would yield a model that overestimated weather's impact on the NAS. To further complicate matters, the same research suggests that pilots' convective weather avoidance decision making also appears to be affected by variables other than purely meteorological variables.

Rhoda and Pawlak (1999) analyzed real-world traffic flows over nine thunderstorm days (63 hours) in the Dallas-Fort Worth area. The researchers sought to identify some of the variables that affected pilots' decisions to penetrate or deviate around a weather cell, and they explored both meteorological and non-meteorological data. After analyzing the data, Rhoda and Pawlak found several non-meteorological variables that were related to pilots' convective weather avoidance behaviors. For example, Rhoda and Pawlak found that (1) distance from the airport, (2) deviation from scheduled arrival, and (3) presence of a "leader" impacted pilots' convective weather avoidance behaviors. The distance from the airport impacted behaviors in that, when aircraft were approximately 20 miles (or less) from the airport, they were much more likely to penetrate storm cells. For example, aircraft that were approximately six miles from airport penetrated cells more than 90% of the time, whereas aircraft that were approximately 50 miles from the airport penetrated cells about 30% of the time. The deviation from scheduled arrival was important in that, when aircraft were "on schedule," the aircraft were observed penetrating heavy weather 15% of the time. In contrast, 51% of "late" aircraft (i.e., 15 minutes or more behind schedule) penetrated heavy weather. Finally, Rhoda and Pawlak found that the presence of a "leader" impacted decision making. A "leader" was defined as one who flew a route that had not been used for the previous ten minutes, and a "follower" was defined as one who flew a route that another aircraft had used within the previous ten minutes. Using these definitions, the researchers found only 27% of "leaders" that encountered heavy weather penetrated it, whereas 56% of "followers" penetrated heavy weather.

In light of the Rhoda and Pawlak study (1999), a model such as CWAM certainly requires input above and beyond the previously mentioned FAA recommendations and probably should contain both meteorological and non-meteorological variables. At present, CWAM includes several meteorological variables (e.g., echo top height and lightning), and the model has demonstrated predictive utility achieving error rates below 25% (cf., DeLaura & Evans, 2006). The model may be enhanced if other variables are added to it, particularly if the variables have high predictive power. In addition, the model might be enhanced if variables are added that are more "comprehensive" in nature and would allow some of the less comprehensive variables to be dropped from the model. With few "powerful" variables (vs. many less "powerful" variables), CWAM would be more efficient in processing the data. Finally, the model currently does not include any non-meteorological information, and given the results of the Rhoda and Pawlak study, non-meteorological information is a potential source of information that might increase the predictive power of the CWAM model.

The efforts described herein are meant to extend the observational work of Rhoda and Pawlak (1999) by *querying* pilots about their decision-making processes. The real-world data collected by Rhoda and Pawlak are invaluable. However, the Rhoda and Pawlak study was limited in that only the route of the aircraft was analyzed, via ITWS (the Integrated Terminal Weather System) sensors. Therefore, we cannot be certain as to what information (e.g., onboard radar, out-the-window cues, non-meteorological considerations, etc) was used by the pilots in making their decisions as to whether they should deviate or not and how this information was used during the decision making process. To supplement the work of Rhoda and Pawlak, the current efforts are based on information collected *directly* from pilots and other participants in the NAS.

By extending the work of Rhoda and Pawlak (1999), the current efforts are meant to assist in the continued development activities associated with CWAM and the identification of variables that have the potential to increase the predictive power of the model. The current efforts are not aimed at ultimately assessing the predictive value of any newly identified variables; Other researchers at NASA Ames, working in the Intelligent Systems Division, also are working with the CWAM developers at MIT by providing data analysis expertise to develop new and improved statistical methods to verify CWAM. Taken collectively, the team of researchers is aiming to produce a model that would allow air traffic management to be based on relatively direct information (that is, predictions about pilots' deviation behaviors) rather than relatively indirect information (that is, using information about that state of the atmosphere from which ATM is meant to predict pilots' deviation behaviors). If some of the information contained in this report serves as valuable, the CWAM developers will be closer to achieving their goal, which is ultimately to reduce the human's mental workload associated with air traffic management.

Project as Part of Efforts to Develop an Advanced Flight Deck Display of Weather

A workshop served as the forum through which information was gathered directly from pilots and other participants in the NAS, and this effort was supplemented by a survey (described in a later section). In addition to achieving the overall goals of the NGATS ATM Project and supporting the continued development of CWAM, this effort also should serve as valuable for those interested in weather-related flight deck information and displays. The FDDRL develops human-centered prototypes and guidelines for advanced flight deck interfaces that integrate display visualizations, decision support tools, and automation.

For well over a decade, one major effort within the laboratory has been to engage in research and development activities as they related to a cockpit situation display (CSD). In the early years, efforts were directed at developing a user-centered cockpit display of traffic information, but in more recent years, the FDDRL engages in research and development in order to provide an advanced display that provides the flight deck with integrated traffic, weather, and terrain information in a form that supports decision making. The FDDRL's web site (http://human-factors.arc.nasa.gov/ihh/cdti/index.html) provides an overview of many of these activities, including a weather data collection and delivery system that was developed for simulating weather environments with the use of "real" weather data and a sample of the flight deck display of weather that serves as a prototype. (A static snapshot of this prototype weather display also can be seen in the questionnaire; see Appendix E.) The website also contains the group's publications (e.g., Battiste et al., 2000; Granada et al. 2005; Johnson et al. 1997; Johnson et al., 2005). Although the FDDRL members have engaged in many unpublished efforts, only one formal publication (other than the current document) is available at this time to serve as a representation of their attempts to provide the flight deck with an advanced, user-centered display that includes weather information (cf., Comerford, 2004).

Numerous research and development efforts are currently underway that strongly suggest the quality, type, and frequency of weather-related information available to the flight deck is likely to improve in upcoming years. Although many efforts are underway, a few efforts that are directly relevant to the research and development activities of the FDDRL are briefly reviewed in the following paragraphs, in order to provide rationale for the FDDRL's efforts in developing a flight deck display that includes weather information in an advanced form.

The RTCA's Special Committee 206 is working on a joint committee with EUROCAE Working Group 76 (cf., RTCA SC-206, 2007). This joint committee is focusing on aeronautical information services and meteorological data link services in order to "provide access to on-line, real-time, quality information to any aviation user, anytime, anywhere" (p. 2), and the joint committee is working closely with other related committees such as the RTCA's Special Committee 195, which is exploring Automated Meteorological Transmission. Their work strongly suggests that, in the not so distant future, pilots will have the ability to receive in-flight weather information in a manner that is not possible today.

The work coordinated by the JPDO (Joint Planning and Development Office) also is an indication of the general changes that are expected in the NAS, including changes that are related to the delivery and consumption of weather-related information (cf., Joint Planning and Development Office, 2007). The JPDO has been organizing a joint effort between the Departments of Transportation, Defense, Homeland Security, and Commerce, as well as the FAA, NASA, and the White House Office of Science and Technology Policy. In short, the JPDO is organizing coordinated efforts aimed at developing the Next Generation Air Transportation System (NextGen), which is a proposed system of information that will be shared by all aircraft by 2025. This system is meant to support the amount of traffic that is predicted by the year 2025, which may be two to three times greater than what it is at the current time. In terms of weather information, the NextGen Concept of Operations includes major changes in the weather-related architecture (i.e., the hardware, software, integration of information, processing of information, and delivery of information). "Today's complex and costly architecture of point-to-point connections to weather sources [will be] replaced by a single-access approach for all users" (Joint Planning and Development Office, 2007, p. v – vi). These 4D weather sources will be "formed from the merger of automated gridded products, models, climatology, and human forecasters. For example, measured and forecasted winds, temperatures, convection, volcanic ash, icing, and turbulence forecasts, as well as satellite images of cloud tops or satellite-derived products [will be] available and formatted for generation of displays, and for direct integration into automated systems (e.g., systems for planning potential flight routes)" (p. vi).

The FAA's Office of Aviation Safety also is involved in efforts that complement those already described. They are working closely with groups such as the National Center for Atmospheric Research in order to ultimately provide the cockpit with better quality, more frequent, and more abundant information than is available today. The goal of their effort (known as the "Weather in the Cockpit" effort) is to support the needs of the aviation community, with a target date of 2012 (cf., FAA, 2006).

Given the many efforts aimed at increasing the quality, type, and frequency of future in-flight weather-related information, the FDDRL has very strong evidence to suggest that demand for an advanced cockpit display of weather (and the associated in-flight decision tools) will increase in the very near future. Therefore, in addition to providing information for the more global NGATS ATM project and the specific project associated with the Convective Weather Avoidance Model (CWAM), the workshop and survey results described in this paper also serve to assist the FDDRL in identifying the type of information that pilots use in making weather-related, in-flight decisions. This information will allow the FDDRL to continue engaging in research and development aimed at developing algorithms, visualizations, and decision support tools associated with weather-related information. Because of the numerous efforts aimed at enhancing weather-related information for the future NAS, some of the restrictions of current-day weather information (e.g., resolution, update rates, etc) are removed. Therefore, the FDDRL is able to attempt to develop visualizations and tools that support the pilot's weather-related decision making in a manner that is not possible today.

The Research

As previously mentioned, two research endeavors, a workshop and a survey, were undertaken in order to supplement research aimed at understanding the weather-related decision making of pilots. In the following pages, the workshop and survey efforts are summarized. For each research endeavor, information related to the rationale, approach, and method are presented. Thereafter, the findings associated with each endeavor are presented.

An Interactive Workshop on Convective Weather

Participants. Beginning in August of 2007, pilots, air traffic controllers, meteorologists, and dispatchers were contacted and invited to a workshop, to be held in October of 2007. Because the workshop was to be interactive, the invitation list was purposefully kept short.

Ultimately, the number of "core" workshop participants that attended the workshop was 13, and the job categories of the participants were distributed as follows: six pilots, three air traffic controllers, three meteorologists, and one dispatcher. All pilots represented Part 121 passenger operations, but cargo carriers were represented within the other groups. In addition to the "core" participants, seven additional participants were invited and attended the workshop. These seven participants were researchers with expertise in field that is directly related to the workshop goals. Five of these additional participants were employees of or contractors for NASA, including sites other than NASA Ames Research Center. Of the seven additional participants whose current employment was primarily in the research domain, three also were pilots and two also had expertise in meteorology. In addition, a few other researchers from NASA Ames Research Center attended the workshop for intervals of varying lengths. Finally, six members of the FDDRL were present for the duration of the workshop.

Data Collection, Treatment of Data, and Confidentiality. With permission from the attendees, exchanges during the workshop were captured via audio and video digital recordings. This permitted focused attention on the discussions during that workshop and allowed for comprehensive analysis of the discussions at a later date. However, the attendees were provided with a formal promise that the digital recordings would be used only as a tool to later make transcriptions of the workshop. Participants were further promised that all names would be removed from the final transcript, and participants would be identified only by their job titles with a distinguishing alphanumeric character included (e.g., Pilot 1, Pilot 2, etc). Attendees also were asked to promise that, if they shared any information they heard during the workshop, they also would present it in an anonymous form. All attendees agreed to these conditions, as evidenced by their completion of the informed consent form. And, these formal promises were honored by the authors of this paper.

Overview of Workshop Activities. On October 25th and 26th of 2007, the FDDRL hosted a workshop at the NASA Ames Research Center. Each day of the two-day workshop yielded an approximately 8-hour working day. The primary goal of the workshop was to focus on pilot decision making as it relates to convective weather. In short, the workshop was meant to serve as a mechanism for data collection, and the participants were made aware of the interactive nature of the workshop in advance. Therefore, unlike many traditional workshops, the number of formal presentations was kept at a minimum. However, on the first day, a few foundational presentations were used to provide the participants with background about the FDDRL, in general, and the goals of the current efforts. In addition, the morning presentations exposed the participants to some of the ongoing research activities at MIT, Lincoln Laboratory, as described in an earlier portion of this document.

With the exception of a tour of the FDDRL's facilities at the end of the second day, the remaining time was dedicated to an interactive, data-collection activity. This primary activity is described in a following section. First, however, the generation of the supplementary materials is discussed.

Materials Used for the Primary Workshop Activity. This workshop was partially aimed at supplementing the work of Rhoda and Pawlak (1999). A situation was generated that was consistent with one of the days on which Rhoda and Pawlak collected data. After reviewing the animated records of the flights analyzed by Rhoda and Pawlak, members of the FDDRL chose to mimic the weather situation of May 9, 1997, and among the aircraft analyzed by Rhoda and Pawlak on that day (i.e., of all aircraft identified as having entered the DFW TRACON intending to land at the DFW or Dallas Love airports), one aircraft was identified as the "target" aircraft.

Although the entire flight plan for the "target" aircraft was unavailable, members of the FDDRL worked with an active Part 121 (passenger) pilot who volunteered to assist in the creation of a realistic flight plan for the aircraft. Using the portion of the flight path that had been recorded in 1997 by Rhoda and Pawlak (including the arrival of the target aircraft at the DFW TRACON), a reasonable flight plan was created, and the imaginary flight was given a departure location. An actual dispatcher report from the volunteer pilot's airline was altered to create a dispatcher's report for this imaginary flight. On the altered dispatcher's report, the call sign of the aircraft was altered such that it would not be associated with any of the "real world" information (i.e., the actual aircraft in the Rhoda and Pawlak study or the flight that was represented on the original dispatch report).

In order to provide workshop participants with as much "real world" data as possible, participants were provided with snapshots of actual NexRad images (of the continental US) from May 9, 1997. The images were provided for two separate time periods that both fell within the time frame for the imaginary flight, and actual satellite imagery was provided for three time periods that fell within the time frame for the imaginary flight. Of course, all of the information workshop participants actually would have had available to them (in flight) could not be provided. However, the limited information added structure and realism to the discussions.

Implementation of "A Day in the Life" Exercise. Workshop participants were given a packet containing the materials (i.e., the dispatch report, NexRad images, and satellite images). They were asked to refrain from viewing the materials until they received an explanation of the exercise. Participants were told that all attendees would begin and "move through" an imaginary day together and that the information in their packets would serve to "set up" the common day. In order to assist in simulating the day, the participants were told that the course of an imaginary flight would serve as the "anchor" for the discussions, and weather-related decision making would be considered during the various phases of flight. Given the aircraft used for the imaginary flight, participants were told to assume the discussions centered on Part 121 operations. Participants also were told that, in order to gain a comprehensive understanding of the effects of all "players" within the NAS, all participants could help by sharing their respective comments, as the pilots moved from the pre-flight planning to the landing phase.

The packets given to participants also contained a set of questions for attendees to consider. Participants were asked to read these questions when they reviewed the other materials. However, these questions were not formally used as part of the later discussions but were included in order to provide the participants with an idea as to the type of information that might be useful to the researchers. Two sets of questions were generated; all participants received both sets of questions. The questions, which served only as guides for the participants, are included in Appendix A.

Participants were given a 15-minute break to review the materials that were provided. Upon their return on the afternoon of the first workshop day, the discussions began and were continued for most of the remainder of the workshop. Using the imaginary flight as an "anchor," weather-related decision making and information gathering activities were discussed, with questions being asked by researchers throughout the discussion. Members of the FDDRL facilitated the discussion by attempting to focus the discussion on weather-related decision making and by maintaining continuity with the imaginary flight (e.g., ensuring the imaginary flight moved along its course when the conversation stagnated at one phase of flight).

Rationale for "A Day in the Life" Exercise. A multitude of workshops specific to weather-related aviation could be cited here, which initially might appear redundant or similar to the current workshop. However, the authors believe this workshop was unique because the activity:

- was one that was used for a very large portion of the workshop,
- was an attempt at data collection,
- included active "players" in the current NAS,
- utilized the course of an imaginary flight, and
- was one in which *all* "parties" (pilots, air traffic controllers, meteorologists, and dispatchers) engaged in an activity *simultaneously*.

To elaborate, this workshop was unlike many "traditional" workshops in that the *majority* of the workshop was spent in an interactive discussion; most traditional workshops dedicate only the final portions of the workshop to "break out" groups in which experts and researchers "brainstorm" regarding a particular set of questions or problems. The majority of this workshop was dedicated to information gathering, and those who were sharing the information were persons who were actively taking part in the current-day NAS. Specifically, this workshop was a form of qualitative research in which data were collected, as opposed to the idea-generation activities in a typical workshop. In addition, the course of an imaginary flight allowed the group to "move through" the phases of a flight. The authors thought this approach might yield fruitful information, because such an approach might encourage detailed responses (vs. generalities). Finally, during the exercise, those with different roles in the NAS shared information using a common framework, allowing shared information to be more consistent with the cooperative activities that occur within the current-day NAS.

Because this approach may be unique (or one of only a few of its kind), the hope was that the workshop would yield unique data. As was shared with the pilots during the preparatory presentations and as mentioned in a previous section of this document, empirical data challenges the notion that pilots consistently adhere to the guidance put forth in the FAA Aeronautical Information Manual regarding convective weather avoidance (e.g., Rhoda and Pawlak, 1999). As detailed in the final section of this paper, the authors intend to utilize several methods in order to understand the type of information pilots *truly* use for decision making in the presence of convection. The "A Day in the Life" approach described herein represents one of these attempts.

Data Analysis. After the workshop, the dialogue from the audio and video recordings was transcribed and resulted in a 400-page word processing document for the first day of the workshop and a 397-page word processing document for the second day. The transcript documents were reduced by one of the authors to capture the major points discussed during the workshop. These major points were categorized by phase of flight, in order to be consistent with the discussions during the workshop. A convenient outcome of this categorization is that these results can be compared with the results of the survey research. The preliminary results of this survey research are summarized later in this document. In addition to categorizing the major points by phase of flight, discussion points were further categorized within each phase of flight to impose organization on the qualitative data. After the first researcher engaged in these activities, another researcher served as a second reviewer. The final product resulted in a summary document, which contains summaries of workshop discussions, paraphrasing of participant comments, and in some cases, direct quotes from workshop participants. When direct quotes were included in the summary document, the researchers insured the identity of the participant would not be divulged.

Workshop Findings. For a brief preview, Table 1 presents the manner in which the data collected from pilots ultimately were organized. For each phase of flight, the table presents the categories into which the qualitative data fell. Although the transcripts cannot be shared due to issues of confidentiality, ***the complete summary document appears in Appendix B***. In the appendix, more detailed information is associated with each of the categories found in Table 1.

Pre-flight Planning: Information from NOAA's Website Packet from Dispatch Coordination with Dispatch	En route, 600 NM (2 hour) from Destination Airport Pilot's Preference in Gathering Information General Meteorological Information Fuel Surrounding Traffic Onboard Radar Information Coordination with Dispatch Timing/Location of the Storm Decision Making "Rules of Thumb"
Departure/Early En route Weather at Departure Airport Weather at Arrival Airport	
En route Fuel Surrounding Traffic Onboard Radar Information Coordination with Dispatch Information from ATC Delays Weather at Arrival Airport	Top of Descent (TOD), 200 NM from Destination Airport Pilot's Preference in Gathering Information General Meteorological Information Fuel Surrounding Traffic Onboard Radar Information Information from ATC Aircraft Schedule Connecting Flights Out-the-Window Cues Decision Making "Rules of Thumb"

Table 1. Categories of Variables Used in Pilots' Weather-Related Decisions as a Function of Phase of Flight

Much of the information in Appendix B will be of use to the FDDRL in considering the design of an advanced flight deck display that includes weather, and hopefully, will be of use to any party interested in the information requirements associated with weather-related decision making. And, the information contained herein may be of use to those working with concepts similar to those that were described in the context of NGATS or NextGen concepts. As the data are presented in Appendix B, they should "stand on their own," with little interpretation necessary for most purposes. However, a few interpretive remarks might be useful. Specifically, in the following pages, the results of the workshop are interpreted in the context of the aforementioned Rhoda and Pawlak (1999) findings. Thereafter, some suggestions are presented for the manner in which these data might be used as part of the CWAM development and predictive models, in general.

The data in Appendix B represent, at least, some of the variables pilots consider in making weather-related decisions. Some of this information may be novel in terms of documenting these processes. In addition, some of the information is consistent with the objective data collected by Rhoda and Pawlak (1999). Interestingly, the only information about Rhoda and Pawlak's study that was shared with pilots *before* the workshop exercise was in the form of a PowerPoint slide, and that slide contained only the following information:

- We are hoping we can determine the type of information pilots ***truly*** use for decision making in the presence of convection.
    - Empirical data challenges the notion that pilots consistently adhere to the guidance put forth in the FAA Aeronautical Information Manual (regarding convective weather avoidance) (e.g., Rhoda and Pawlak, 1999)

Near the end of the workshop exercise, pilots discussed their decisions from the top-of-descent to the landing phases of flight. Only at this time were pilots shown an animation of the traffic data Rhoda and Pawlak collected. However, at this time, pilots had not yet been exposed to the findings of their research in terms of variables and statistics. *After* the exercise, Rhoda and Pawlak's findings were summarized. Yet, the qualitative data contain references to some of the variables that Rhoda and Pawlak had found to be important in their analysis of real-world traffic flows.

Throughout the transcripts and as reflected in Appendix B, clear evidence is found that distance from the airport affects pilots' decision making. Specifically, an examination of Appendix B demonstrates that different variables are considered by pilots as a function of phase of flight, and the differences between the phases of flight suggests that distance from the destination airport would, in fact, affect pilots' decision making. In addition, evidence was gathered to suggest that the presence of a leader affects pilots' weather-related decisions. One obvious reason the behaviors of other aircraft might be considered ("what are the other aircraft doing?") is that, if one aircraft makes its way safely through a particular portion of airspace, the probability of another safely making its way through airspace may be greater. However, the following direct excerpt from the workshop transcripts serves to supplement the information in Appendix B, because it serves as another potential and very practical explanation as to why these follow-the-leader behaviors may be occurring:

> "A large perspective look at decision making, another element of that is justifying your actions. During the inquiry, to justify your actions, if you can go, you know, I was in trail with a bunch of guys, everybody's making it through, all the other parameters were good when I started through that, it looked good. There was no reason to expect that I was going to go through a hail shaft and trash this airplane versus I went through it no problem versus I'm going to go out and try a different route. You go out and try that other route as the path finder and find a hail shaft at that time, and then try to justify your actions. [You might hear someone saying to you] So let me get this straight, there were six airplanes in front of you that made it okay and six that were behind you that made it okay, and you went another way?"

In other words, follow-the-leader behaviors may occur because a "follower" gains useful information from a "leader" (i.e., the path was safe). However, this quote suggests that follow-the-leader behaviors may be a result of pilots' concerns about accountability. At this point, it is unclear as to whether pilots simultaneously consider the information gained from the successful flight of a leader and issues of accountability in making decisions in such a context. However, if further research indicates the latter (concern about accountability) is weighted heavily or considered solely in making decisions, such a state of affairs may be reason for concern. For centuries, research in social psychology has demonstrated that ignoring relevant information in favor of "doing what everyone else is doing" can yield disastrous outcomes (cf., Aronson, Wilson, & Akert, 2007).

Consistent with Rhoda and Pawlak's objective findings (1999), workshop findings also indicate that the deviation from scheduled arrival affects decision making for, at least, some pilots. As reflected in Appendix B, some pilots claim their decisions are not affected by the pressures of scheduled arrival time, but others suggest scheduled arrival time does, in fact, affect their decisions. The appendix presents a quote in which a pilot explained why the potential for his own misconnects (i.e., missing his connection at the current destination airport) would affect his decisions. Another pilot suggested that deviation from scheduled arrival does not affect his decisions, but despite this claim, this quote serves to illustrate that this pilot does, at least, recognize the variable:

> "When we change over en route, we send the company a message telling them approximately what our touch down time is. We get connecting gates. So we're painfully aware. You know, you get a print-out two or three feet long showing you where all of the people behind you are going...I'm going to take the longer route if it's the safest thing to do, bottom line...But still, how are you going to explain the numbers."

In addition to finding corroboration for Rhoda and Pawlak's results (1999), the workshop findings also may yield fruitful information in the development of CWAM. Some relevant interpretations and suggestions are provided, but a first-hand inspection of Appendix B also might be of use to researchers interested in CWAM or any other model attempting to make predictions about pilot's decisions in the face of weather. However, in order to support direct implications for a predictive model, such as CWAM, the results of the workshop were reorganized.

In Appendix C, numerous portions from Appendix B have been reproduced in a tabular format. These portions of the text represent ***points that have potential to be quantified in a predictive model, such as CWAM***. In some cases, comments are provided that are brief explanations as to how these concepts might be quantified and/or why these concepts might be important to incorporate in a predictive model of pilots' weather-related decisions.

To supplement the information in Appendix C, two specific recommendations are provided here for consideration in a modeling effort, such as CWAM. *First*, because the information in Appendix C is organized by phase of flight, any potential variable within the table might provide greater predictive power if it is limited to the phase of flight to which it corresponds. (Because this workshop was a first attempt, of course it was impossible to gather all relevant information. However, some of the information could be validated easily or expanded upon by experts within the context of Appendix C.) *Second*, within the table, several references are made to pre-existing, National Weather Service products. Some potential exists in current-day weather products that "try to mimic the expertise and experience of the meteorologist, using the same data sources and diagnoses known by humans to add skill to the desired product" (Lindholm, 2003, p. 3), and many of these products also provide information for three dimensions. Lindholm provides a succinct review of some of these products, which are available via the National Weather Service. The products may yield fruitful results in that they provide the user (or model) with an overall diagnostic recommendation. A major strength of such products is that they integrate many sources of information and mimic some of the judgments made by experts (with the use of fuzzy logic and the like). A perfect example is the GTG (graphical turbulence guidance) product, which uses many sources to produce one outcome for a given point within three-dimensional space. For example, after integrating numerous sources, "moderate turbulence" might be predicted for a given point in three-dimensional space. These products are expected to continue to improve in terms of their performance, and the second version of the GTG already has been developed.

A short summary of the findings associated with the jobs of the meteorologist and dispatcher can be found in Appendix D. The presence of the meteorologists, dispatchers, and air traffic controllers served to be quite useful in manners other than those represented by Appendix D. As was hoped, the discussions seemed to be more balanced in their presence, in that pilots often interacted with the others in the discussions. From these interactions, the manner in which pilots interact with and are impacted by meteorologists, dispatchers, and air traffic controllers was made clear. And, the pilots appeared to be "cued" to share information, when the perspective of the other "players" in the NAS was shared.

An On-line Survey

Rationale and Goals Specific to the Survey Effort. In order to supplement the qualitative data obtained from the workshop activity, survey research also is being conducted. Of course, like the qualitative data collected during the workshop, the information gathered from questionnaires also is subjective in nature. However, subjective responses are the very type of information that is desirable, in order to supplement the objective data collected by Rhoda and Pawlak (1999) when they analyzed real-world traffic flows. The strength of the approach utilized during the workshop is that the researchers are less likely to miss important information, in that responses are open-ended. On the other hand, a questionnaire provides a more structured medium. The structure imposed by a questionnaire more readily allows for comparisons among participants' responses and for the computation of statistics. Therefore, taken collectively, chances are higher that the information gathered from the two research endeavors represents some of the true processes underlying pilots' weather-related decisions.

Consistent with the overall goals of the project, the survey was meant to gain insight into pilots' weather-related decisions. However, questionnaires must be kept at a reasonable length in order to increase the chances that participants will complete the entire question set. Therefore, survey development must ensure that each question is of high information value, and questions should be posed in a manner that, for each unit of the respondent's time, the researcher can obtain the most amount of information. The researchers attempted to abide by these guidelines in developing the questionnaire described herein.

For this first attempt at collecting survey information on pilots' weather-related decision making, it seemed reasonable to assess the relative importance that pilots attach to the various types of weather-related information. By assessing the importance of information rather than the importance associated with available weather products, some insight into the underlying decision processes might be gained. In addition, by inquiring about information rather than products, any knowledge gained from this survey would not necessarily be limited to current-day operations.

After identifying this general objective, a literature review was completed such that previous efforts were not duplicated. In a paper entitled "Aviation Weather Information Requirements Study," Keel et al. (2000) provide an extensive overview of the many human factors and technological issues related to weather in aviation. One portion of the study is of particular relevance in the current context. Specifically, Keel et al. provide several matrices (cf., pp. 45-49), on which the rows represent various types of weather information (e.g., precipitation, icing, etc) and the columns represent phases of flight (e.g., departure, initial climb, etc). Through a personal communication, the authors learned that Keel et al. consulted with experts and were able to indicate the types of weather information that are important during various phases of flight. This approach seemed to be an efficient and powerful means by which the importance of weather-related information could be assessed. However, Keel et al. did not provide the matrix to respondents, but instead, created these matrices as a means to summarize their findings.

Therefore, a modification of their matrices for data collection was deemed to be an effort that might yield fruitful results. Specifically, in the current research, an adaption of the matrices was presented to survey respondents. In addition, rather than placing flight information into a binary framework (i.e., important or not important), the current research aimed to determine the extent to which information is important.

Further review of the literature yielded another study that used a similar approach (Beringer & Schvaneveldt, 2002). Unlike Keel et al., Beringer and Schvaneveldt collected survey data from pilots, and because the survey asked pilots to rate the importance of each type of weather information, Beringer and Schvaneveldt also provide summary statistics regarding the relative importance weather information by phase of flight. Through personal communication, the authors learned that the Beringer and Schvaneveldt study included only general aviation pilots. Although the FDDRL's research was not meant to exclude any information learned about other types of operations, the current focus was on Part 121 operations. However, the similarity in the approach used by Beringer and Schvaneveldt and the current approach only increased confidence in the method chosen by the FDDRL. Therefore, the current research was similar to the research performed by Keel et al. as well as the research performed by Beringer and Schvaneveldt, but it also yielded novel information.

Development of the Questionnaire. The *first portion of the questionnaire* (see questions 1 through 12 in Appendix E) was meant to collect background information about the persons completing the survey. This information was collected because it would serve to explore potentially interesting differences in responses as a function of the background and experience of the respondents.

The *second portion of the questionnaire* might be considered the "core" portion of the survey. The weather categories used by Keel et al. served as the foundation for the core portion of the weather survey. (See questions 13 through 15 of the questionnaire.) The categories of weather information were adapted (e.g., rephrased or re-categorized) in a few instances, a few categories used by Beringer and Schvaneveldt were included, and a few novel categories were included as well. As can be seen in Appendix E, participants were asked to consider each phase of flight and rate each type of weather information using the following scale:

0 The information is **not important** to the safety or efficiency of the flight. Knowing this information will not affect the flight for good or ill.
1 It would be **nice to have** this information, but it is *not critical* to maintain flight safety.
2 It is **critical for me to have** access to this information, as it will directly influence my ability to *maintain flight safety.*

The *third portion of the questionnaire* (questions 17 through 18) originally was intended to be a separate survey effort but was included because a reasonable questionnaire length was maintained despite the inclusion of the last section. These questions were meant to survey pilots in terms of the types of weather information that they believe should be visualized on a flight deck display.

Recruitment of Respondents, Survey Implementation, and Treatment of Data. A commercial company's tools (SurveyGizmo) were used to create and post the questionnaire online. A major cargo carrier volunteered to advertise the survey to employees via the company's internal website and both the electronic and paper versions of the company's newsletter. In addition, the Director of Dispatch for a major airline volunteered to invite employees of the airline to participate. Finally, participants of the previously described workshop were invited to complete the online survey, if they were interested in doing so at some time after the completion of the workshop. All of the aforementioned attempts at recruiting respondents directed interested parties to the online link associated with the questionnaire.

Besides the background information respondents' included in the survey, no information was collected that would allow for a respondent to be identified. The anonymity was considered to be important to encourage respondents to be completely truthful in their responses. Data were encrypted for secure collection. Even the company (whose services were being used to collect that data) was unable to access the data.

Preliminary Results. The authors intend to continue survey data collection in the future. At present, the data represent 12 respondents who engage in Part 121 operations. ***Appendix F includes these preliminary data in a tabular form***. The number in each cell represents the percentage of respondents that rated a particular weather phenomenon as being "critical" (vs. "not important" or "nice to have"). Most cells in the table represent 12 responses, although in a few cases only 11 of the 12 pilots provided a response. In order to be consistent, then, the data are presented as percentages. Inferential statistics are not yet appropriate, as statistical power would be low. Black, bolded boxes represent any cell that yielded a response greater than 70%, and these data should serve to provide an indication of general tendencies in responses. In short, these initial summary data could be used to identify important variables as a function of phase of flight for use in a predictive model. In addition, these data could be utilized in the development of cockpit display of weather information and may provide guidance as to the necessity of variables in various phases of flight. This information would be of use in attempting to maintain an uncluttered cockpit display.

Future Directions and Closing Remarks

The FDDRL members hope to contribute to the rapidly-growing knowledge base that is dedicated to advancements in aviation weather. In order to do so, we are hoping to continue the in-progress survey data collection and follow-up on the workshop findings. Specifically, it might serve particularly useful to have a "mini" workshop to which only very few pilots were invited (e.g., 3 or 4), and with those pilots, the researchers believe it would be useful to work from the pre-existing workshop findings and the survey data. This effort would allow us to obtain a greater understanding of the information with which we have been provided and to engage in discussions that were structured in a manner that we now know represents what pilots experience. In addition, the FDDRL is planning to conduct interviews with Part 121 pilots after they experience an actual weather event during a flight, and one of the cognitive interview techniques will be utilized for data collection. These interviews may serve to extend the findings presented herein. The authors believe knowledge elicitation may be most successful if a variety of techniques are utilized. Finally, the FDDRL intends to engage in archival research to determine if documented incidents and accidents might yield insight into the variables that affect pilots' weather-related decision making.

The authors are hopeful that "next generation concepts," such as those described in the first portion of this paper, will be realized in the not-so-distant future. As summarized by Lindholm (2003), future plans for the delivery and consumption of weather products poses some problems. However, in agreement with Lindholm, the current researchers believe one of the biggest challenges in moving toward a model that appropriately utilizes decision support systems and automation is identifying human factors issues and the manner in which humans currently digest weather information.

References

Aronson, E., Wilson, T.D., & Akert, R.M. (2007). *Social psychology* (5th ed.). Englewood Cliffs, NJ: Prentice Hall.

Battiste, V., Johnson, W., & Holland Bochow, S. (2000). *Enabling strategic flight deck route re-planning within a modified ATC environment: The display of 4-D intent information on a CSD.* NASA-TM 2000-01-5573. Moffett Field, CA: NASA Ames Research Center.

Beringer, D. & Ball, J.D. (2004). *The effects of NEXRAD graphical data resolution and direct weather viewing on pilots' judgments of weather severity and their willingness to continue a flight.* Tech. Report DOT/FAA/AM-04/5. Federal Aviation Administration.

Beringer, D. & Schvaneveldt, R. (2002). Priorities of weather information in various phases of flight. *Proceedings of the Human Factors and Ergonomics Society 46^th^ Annual Meeting*, Santa Monica, CA.

Comerford, D. (2004). *Recommendations for a cockpit display that integrates weather information with traffic information.* NASA-TM 2004-212830. Moffett Field, CA: NASA Ames Research Center.

DeLaura, R., & Evans, J. (2006). An exploratory study of modeling enroute pilot convective storm flight deviation behavior. *American Meteorological Society's 12th Aviation, Range and Aviation Meteorology*, Atlanta, GA.

Federal Aviation Administration. (2006, November 15). *Weather in the Cockpit: Concept of Operations.* Retrieved March 15, 2008, http://www.ral.ucar.edu/projects/wic/

Granada, S., Dao, A. Q., Wong, D., Johnson, W. W., & Battiste, V. (2005). Development and integration of a human-centered volumetric cockpit display for distributed air-ground operations. *Proceedings of the 12th International Symposium on Aviation Psychology,* Oklahoma City, OK.

Johnson, W.W., Battiste, V., Delzell, S., Holland, S., Belcher, S. Jordan, K. (1997). Development and demonstration of a prototype free flight cockpit display of traffic information. *Proceedings of the 1997 SAE/AIAA World Aviation Congress,* Anaheim, CA.

Johnson, W. W., Battiste, V., Granada, S., Johnson, N., Dao, A. Q., Wong, D., & Tang, A. (2005). A simulation evaluation of a human-centered approach to flight deck procedures and automation for en route free maneuvering. *Proceedings of the 12th International Symposium on Aviation Psychology,* Oklahoma City, OK.

Joint Planning and Development Office. (2007, June 13). *Concept of Operations for the Next Generation Air Transportation System.* Retrieved March 11, 2008, http://jpdo.gov/library/NextGen_v2.0.pdf.

Keel, B.M., Stancil, C.E., Eckert, C.A., Brown, S.M., Gimmestad, G.G., & Richards, M.A. (2000). *Aviation weather information requirements study.* NASA-TM 2000-210288. Hampton, VA: NASA Langley Research Center.

Lindholm, T. (2003). Air traffic management decision support using integrated methods of diagnosing and forecasting aviation weather. *International Air Traffic Conference*, Budapest, Hungary.

Rhoda, D. A. & Pawlak, M. L. (1999). *An assessment of thunderstorm penetrations and deviations by commercial aircraft in the terminal area.* Tech. Report NASA/A-2. Lexington, MA: Massachusetts Institute of Technology, Lincoln Laboratory.

RTCA SC-206 (2007). *Terms of reference: Joint RTCA special committee 206 / EUROCAE working group 44/76, aeronautical information services (AIS) and meteorological data link services.* RTCA Paper No. 301-07/PMC-585. Washington, D.C.: RTCA.

Swenson, H., Barhydt, R., & Landis, M. (2006). *Next Generation Air Transportation System (NGATS) Air Traffic Management (ATM)-Airspace Project: Reference Material. External Release Version.* Retrieved February 7, 2009 from http://www.aeronautics.nasa.gov/nra_pdf/airspace_project_c1.pdf.

Appendix A: Questions Meant to Guide Workshop Participants

<u>Questions for Pilots to Consider</u>

- What affects your decisions as to whether or not you will deviate around convective weather?
- What *meteorological variables* do you consider and actually utilize in convective weather avoidance decision making?
    - *Weather Products*: What weather products do you use? How are they presented? How often are they provided? Who initiates the process by which you come to know about the information contained within the weather product? How do you learn about the "age" of these products? How much does the "age" of a product affect your decisions and in what way?
    - What meteorological variables do you consider other than those represented by a formal weather product?
- What *non-meteorological* variables do you consider and actually utilize in convective weather avoidance decision making?
- How do others in the air traffic system affect your convective weather avoidance decision making?
- What information do you use to decide whether or not you will enter into and pass through a region where the tops are near flight level (and where it is likely that visibility will be significantly reduced)?
- In terms of convective activity, how close do you fly to "hazardous" weather? How do *you* define hazardous weather in this context?
- At what distance from convective weather do you decide whether or not you will deviate around the convective weather? What variables affect the distance at which you make the decision?

<u>Questions for Others to Consider</u>

- How are your decisions affecting a pilot's convective weather avoidance decision making?
- How might a pilot (or pilots) convective weather avoidance decision making affect your decision making?
- How do you interact with pilots to support their decision making (if at all)?

Appendix B: Summary of Workshop Findings (Pilot Variables)

Variables Used in Pilots' Weather-Related Decisions as a Function of Phase of Flight

Note: The following data are a summary of pilot responses that were based on a workshop scenario was adapted from a real-world weather event (cf., Rhoda & Pawlak, 1999). The weather event was composed of thunderstorms that were active in the Dallas-Fort Worth area. The workshop scenario was created such that the flight under consideration was one destined for DFW on this day of thunderstorm activity.

Pre-flight Planning:

Information from NOAA's Website

- "Big weather patterns"
- Areas that may have turbulence
- Existence/location of hurricanes, typhoons, and storms
- Existence/location of storms as they relate to planned flight path

Packet from Dispatch

- Pilot's approach in using the information
    - Some pilots
        - read every line of the report.
        - don't look at every line of the report.
            - *Example: "You don't look at every single line, you look at what is relevant to you, and as things become relevant, you'll review it in greater detail."*
- Departure station weather
- Destination weather
- Turbulence
    - Upper/lower boundaries
- Jet streams
- Convective activity
- Winds
- Fuel
- Alternates

Coordination with Dispatch

- Pilot's planned "approach" in dealing with the weather situation
  - One of the following two approaches is used:
    - Get close to the weather and attempt to "go through holes"
      - Action may not necessarily be taken at this time; relevant variables might not be considered until en route.
      - May want to discuss fuel with dispatcher nevertheless.
    - Decide at this time to "go around" weather
      - Consider fuel with dispatcher
- Fuel
  - If it is likely that pilot is heading into "big weather," pilot asks dispatch to add fuel to standard fuel supply.
    - Allows pilot to be certain that fuel is sufficient if they need to go around the weather or hold.

Departure/Early En route

Weather at Departure Airport

- Runway status (wet or dry)
- Conditions as they relate to the need for engine or wing anti-icing
- Winds for take off
- Weather activity over departing airport
- Information from those that recently departed or landed at the airport
  - Example: What was the ride like, and what was your crossing?

Weather at Arrival Airport

- Some pilots consider this variable at this time.
  - Are other flights landing at arrival airport or are they diverting?
- Some pilots say weather delays at arrival airport are merely in the "background" of their minds at departure time.
  - "You don't go into great detail over it." The weather will either get better, worse, or stay the same; it's dynamic, so you'll get into more detailed information when you get closer.

En route

Fuel

- Reroute in flight
  - Major reroute
    - Ask dispatch to ensure fuel conditions meet new route needs.
  - Minor deviation
    - No need to coordinate with dispatch.

Surrounding Traffic

- Most decisions are influenced by what you see ATC doing with aircraft ahead of you.

Onboard Radar Information

- Used when weather is close enough to "paint."
  - Maneuvering becomes tactical.
- Information is combined with information obtained from ATC, in order to avoid "bad" parts of storm.

Coordination with Dispatch

- ATC communication about re-routing may come from dispatch if several flights need to be re-routed.
- Information from dispatch early on (say 640nm out) is used for strategic planning.
  - May not make a route change from merely hearing weather info from dispatch.
  - Keep checking because, when tactical maneuvering may be required later, the pilot should already have gathered all relevant information about the possible maneuvers available based on variables such as:
    - fuel burn
    - possible distance to alternate

Information from ATC

- Communications increase as navigation around weather becomes tactical.
- ATC mental workload
  - Affects requests pilots make for navigation.
- When working tactically with weather, ATC information is combined with information obtained from onboard radar, in order to avoid "bad" parts of storm.
- ATC describes 4, 5 or 6 points with tops.
  - Pilots input the information into the FMS to overlay graphically on route.
  - Limited use because it's 2-dimensional.
    - "But we have to remember that the tops aren't the 35,000 feet at every square inch within this square."

Delays

- Delays confirm the weather picture.
  - You know it is "bad" if you're being delayed.

Weather at Arrival Airport

- PIREPS associated with arrival airport
- Traffic flow at arrival airport
  - Are other flights landing at arrival airport or are they diverting?

<u>En route, 600 NM (2 hour) from Destination Airport</u>

Pilot's Preference in Gathering Information

- Some pilots
  - believe 600nm is still too far from the storm to make a decision.
    - They suggest that, even when you're descending down into it, you're learning as you go.
  - discussed decision making at this time/distance.

General Meteorological Information

- Clouds
  - How are they forming?
- Winds
  - How are the winds going to affect whether I should go north or south?
- Tops
  - How high?
    - Can my aircraft climb over them?
      - Are we too heavy? Are we above our habitable altitude?
  - What are the icing risks if I climb over them?
- Icing
  - "Icing is as much a threat as turbulence."
- Storm growth or decay
- Turbulence
  - Example: The biggest thing to stay away from is turbulence (you're not flying in a thunderstorm, period), so you may need to ask for a 90 degree vector to get out of turbulence and you learn as you go.

Fuel

- How does the fuel affect how I should maneuver (e.g., north or south)?
  - "The fuel gage kind of gets very paramount in your mind" when confronted with a storm.

Surrounding Traffic

- How are other aircraft getting in?
  - Tops
    - Are they going over the tops?
    - Is there enough room for them to go over?
    - Are they going down?
  - Are they working their way through them?
  - Are they going around, south or north?
  - What are people doing at my altitude?
- Which flight level is bumpy, which is not?

Onboard Radar Information

- If deviation is not possible, work off the radar image
  - Try to calibrate the intensity level of your level while flying.
- Acquire "crude" estimate of storm intensity, growth, and tops
  - Raise or lower the tilt of the antenna and see if the storm is actually staying the same in intensity.
    - Is it growing? Or, is it getting smaller as you approach it?
      - If it's getting smaller as you keep getting closer in, you scale down, if the storm is getting smaller, then that's telling you are at least on top of it or should clear.
        - And that's a very loose variable, because you don't know if it's growing at 6,000 to 10,000 feet or maybe it's a mature storm and it's now in the decay stage.

Coordination with Dispatch

- Information sometimes sent hourly (via text message)
    - Radar information
    - Line/front of storm
    - Tops
    - Information about the corner post you may use to enter
    - Weather warnings
- Weather-related information, as requested from pilot (via text message)
- If other aircraft are entering TRACON on a route other than the one that was planned, dispatcher:
    - discussing plan with pilot as early as one hour away from arrival.
    - works out:
        - fuel burn
        - timing for the new route

Timing/Location of the Storm

- Affects overall predictions about the storm
    - "In this example, it would be springtime cold air coming from the north. You've got warm gulf air moving north. What happens in development is going to be from north to south along this front. If this system were in Chicago, the development would be opposite. If it is 2:00 in the afternoon, you're going to see development/storms popping up all the way to the south down to the Mexican border."

Decision Making "Rules of Thumb"

- "The whole 20NM thing doesn't matter if we're [approaching a] line of thunderstorms and you're flying around just looking at them, looking at the radar...I really try to [abide by the 20] nautical mile rule. Sometimes it doesn't work."
- If you're nearing the storm, you try whatever you can to stay visual.
- If you are asked to start down early, ask for a vector to "go around" rather than go into a serious under cast that can't be seen by the pilot.
- Altitude is the preferred deviation method, if it is possible.
    - Rationale: because pilots can stay above the storm and usually stay on route.
    - Depends on:
        - where the storm is relative to the flight plan (if it makes sense to stay up)
        - how the convective weather is building.
            - You don't want to go above and be hit with a rapidly building cell.
- If deviation is not possible (e.g., it is a wall, 200 – 300 mile line, 30 miles deep and up to 40,000), then
    - simply have to pick the weakest hole.
    - work off the radar image (as described under a previous section labeled "Onboard Radar Information").

Decision Making "Rules of Thumb" contd.

- "If the weather is a "couple miles out and the weather is en route, it would probably be better to go ahead and take a heading change to avoid it generally."
  - "I can make a two or three-degree change right now that's not going to cause my fuel to burn anything,"
- If you're close to a terminal, you don't want to climb just to come right back down.
  - A small 5 degree cut may be the best thing to do early enough.
- If I am given a radar vector, is there a choice in maneuver?
  - If I have a choice, I go upwind based on rules in my SOP's (standard operating procedures).

Top of Descent (TOD), 200 NM from Destination Airport

Pilot's Preference in Gathering Information

- Some pilots believe:
  - approaching TOD is when you start making a decision to stay on route, or deviate.
  - decision making begins in previous phase (see earlier comment).

General Meteorological Information

- Turbulence
  - Guidance is to try and avoid moderate turbulence, even on the climb and descent.
  - You may need to get through it for a short duration.
    - For guidance, pilots actually pay attention to the words (e.g., "moderate" or "severe"), rather than the numbers associated with the scale.
      - Moderate or severe turbulence
        - en route may be taken if it is clear on the other side
        - probably wouldn't take it on landing.
- Not allowed to land if:
  - Windshear alert
  - Microburst alert
- "No one will penetrate a level 4 or 5 cell"

Fuel

- Determines how far you are able to deviate.
- If you are already late, you will be that much lower on fuel.
  - Increases motivation to "get in."
- If you come in with minimal fuel, you might talk to dispatch and see if they can put you ahead of another flight.

Surrounding Traffic

- Usually the first pilot makes a decision.
  - "Hey I can't go there; I can go this way."
    - ATC allows that decision.
    - Then every aircraft after follows that line of action.
      - Aircraft do NOT follow the lead if:
        - Something is obviously "wrong" with the path
          - "That it can fill in within seconds."
        - Your own aircraft cannot follow it, for whatever reason

Onboard Radar Information

- Turned on when:
  - pilot knows there is weather about which he/she should be concerned.
  - over water or at night
    - because it helps detect any "surprises" that might be lurking out there.
- Some radars now detect turbulence.

Information from ATC

- When weather is an active factor,
  - usually the pilot's plan of action agrees with ATC.
    - So, pilots "go right along with it."
  - pilots "weight" their own information more heavily than ATCs weather-related information.
    - ATC weather displays provide stale weather data.
      - The pilot's information is more current.
      - Sometimes ATC doesn't even have weather "up" on the display.
      - Sometimes ATC vectors pilots through weather, which ATC can't see because their radar is for separating aircraft.
        - There is a really poor weather detector.

Aircraft Schedule

- Willingness to penetrate bad weather increases if you're behind schedule.
  - Some pilots said they agreed with the previous statement, while others did not.
  - A flight is considered "delayed" if it is 15 minutes or more behind schedule.

Connecting Flights

- Passengers' connecting flights.
  - Pilots are aware of connecting flight schedules for passengers, however, "you're going to take a longer route if it is the safest thing to do, bottom line."
- Pilot's connecting flights
  - Some pilots claim it does not affect decision making
    - "…on time, not on time, who went ahead of me, who's behind… none of these factors enter into my personal decision on how I operate my plane. There is no compromise to safety."
  - Other pilots claim it does affect decision making
    - "If it's the last trip of the month, I can't make that trip up. Not only have I missed my flight, I'm also docked for pay. So there's consideration."

Out-the-Window Cues

- This information is weighted more heavily than the onboard radar information.
  - "… your eyes give you a better conception than what the radar has, to be honest with you."
- If in thick weather, look for a path down.
- If "there's no convective activity directly in your flight path. [then] you'll take a little bit of moderate rain."
- You do not go to places where you see:
  - cloud-to-ground lightning
  - cloud-to-cloud lightning
  - a thick, black rain shaft

Decision Making "Rules of Thumb"

- Once you start descending, you make lateral maneuvers.
  - You would not make a vertical because you're coming down and others are going out.
  - You might make changes in descent rate
    - For example: hold at 20 before going down to 10.

Appendix C: Potential Concepts for "Quantification" of Pilots' Weather-related Decisions

Phase of Flight	Workshop Finding	Comments
En route	Most decisions are influenced by what you see ATC doing with aircraft ahead of you.	• Consistent with Rhoda and Pawlak findings
En route	Are other flights landing at arrival airport or are they diverting?	• Consistent with Rhoda and Pawlak findings • Easily quantifiable (e.g., percent)
En route, 600 NM (2 hour) from Destination Airport	Tops • How high? • Can my aircraft climb over them? • Are we too heavy? Are we above our habitable altitude? • What are the icing risks if I climb over them?	• If aircraft specifications are available, these questions could be used to predict whether a pilot might choose to "climb over" the tops.
En route, 600 NM (2 hour) from Destination Airport	Tops • What are the icing risks if I climb over them?	• Weather products (e.g., the NWS's CIP) could be used to take a "best guess" at how the pilot might answer this question.
En route, 600 NM (2 hour) from Destination Airport	Storm Growth or Decay	• This meteorological information might assist in predicting behavior (e.g., climbing or penetrating).
En route, 600 NM (2 hour) from Destination Airport	Turbulence	• See later comment on turbulence, where more detailed information was obtained.
En route, 600 NM (2 hour) from Destination Airport	How does the fuel affect how I should maneuver (e.g., north or south)?	• Fuel was a recurring "theme" in the workshop. • If fuel information (or estimates) were available, (at least) the "allowable" and "impossible" maneuvers might be identifiable.

En route, 600 NM (2 hour) from Destination Airport	How are other aircraft getting in?
	• Tops
	  o Are they going over the tops?
	  o Are they going down?
	  o Are they working their way through them?
	  o Are they going around, south or north?
	• What are people doing at my altitude?
		• This information provides more specific direction for predicting the effects of "tops" information on decisions.
		• Perhaps it is possible to answer some of these questions for "leader" aircraft and apply the predictions to a potential follower.
		• The final point suggests that the actions of those at the ownhship's altitude might be weighted most heavily.

En route, 600 NM (2 hour) from Destination Airport	Which flight level is bumpy, which is not?	• Information could easily be obtained from PIREPs and the like.
En route, 600 NM (2 hour) from Destination Airport	If other aircraft are entering TRACON on a route other than the one that was planned, dispatcher begins discussing plan with pilot as early as one hour away from arrival.	• Information might assist in predicting the timing of some flight plan changes.
En route, 600 NM (2 hour) from Destination Airport	Altitude is the preferred deviation method, if it is possible (doesn't require path deviation). Depends on: • where the storm is relative to the flight plan o "If the weather is a "couple miles out and the weather is en route, it would probably be better to go ahead and take a heading change to avoid it generally." ▪ "I can make a two or three-degree change right now that's not going to cause my fuel to burn anything," o If you're close to a terminal, you don't want to climb just to come right back down.	• Potentially contradictory information here that could be examined by discussions with pilots or testing with predictive models. o If close to the terminal, climbing appears to be undesirable. (This is confirmed below as well.) o If relatively farther from the terminal, one finding suggests altitude changes are preferred (to stay on path), while another suggests very small, early heading changes are preferred.
En route, 600 NM (2 hour) from Destination Airport	If I have a choice, I go upwind based on rules in my SOP's.	• Information might assist in predicting deviations, when appropriate context exists
TOD, 200 NM from Destination Airport	For guidance, pilots actually pay attention to the words (e.g., "moderate" or "severe"), rather than the numbers associated with the scale. • Moderate or severe turbulence en route may be taken if it is clear on the other side o probably wouldn't take it on landing.	• Weather products (e.g., the NWS's GTG, any available advisories, etc) could be used to take a "best guess" at how the pilot might assess the safety of the environment regarding turbulence.
Top of Descent (TOD), 200 NM from Destination Airport	Not allowed to land if: • Windshear alert • Microburst alert	• Information is easily obtainable.
TOD, 200 NM from Destination Airport	"No one will penetrate a level 4 or 5 cell"	• Information is easily obtainable and consistent with well-known "rules of thumb."

TOD, 200 NM from Destination Airport	Determines how far you are able to deviate.	• See earlier comment regarding fuel.
TOD, 200 NM from Destination Airport	If you are already late, you will be that much lower on fuel. • Increases motivation to "get in."	• See earlier comment regarding fuel.
TOD, 200 NM from Destination Airport	Usually the first pilot makes a decision.	• Consistent with Rhoda and Pawlak findings.
TOD, 200 NM from Destination Airport	Aircraft do NOT follow the lead if: • Something is obviously "wrong" with the path • Your own aircraft cannot follow it, for whatever reason	• Although the first bullet is not easily operationalized, it might be possible to determine if a "leader's" maneuver is unobtainable by the target aircraft.
TOD, 200 NM from Destination Airport	Willingness to penetrate bad weather increases if you're behind schedule. • A flight is considered "delayed" if it is 15 minutes or more behind schedule.	• Consistent with Rhoda and Pawlak findings.
TOD, 200 NM from Destination Airport	Pilot's connecting flights	• Some pilots claimed this affected their decisions. • If this information were available, it might be of predictive value.
TOD, 200 NM from Destination Airport	If "there's no convective activity directly in your flight path. [then] you'll take a little bit of moderate rain."	• Provides predictive information in the sense that this situation may yield no deviation.
TOD, 200 NM from Destination Airport	You do not go to places where you see: • cloud-to-ground lightning • cloud-to-cloud lightning • a thick, black rain shaft	• Information in first two bullets may be easily quantifiable from pre-existing sources. • Previous studies on CWAM suggest lighting in not necessarily a powerful predictor (DeLaura & Evans, 2006). o Is it possible that limiting predictions to this phase of flight or a certain distance from storm might affect predictive ability? o Note: in the workshop exercise, distance to storm and phase of flight were confounded (that is, not able to be separated).
TOD, 200 NM from Destination Airport	Once you start descending, • you make lateral maneuvers. • you might make changes in descent rate	• Information provides constraints on behaviors, which might serve as useful in a model.

Appendix D: Summary of Workshop Findings (Dispatcher/Meteorologist Variables)

Dispatcher & Meteorologist: **Preparing Information for Flights**

General Meteorological Information

- Location of fronts
- Winds
- Turbulence
- Thunderstorms
    - Determine if fast- or slow-moving
- Crosswinds at arrival/alternate airports

Weather Products

- TAFs
- METARs
- NOTAMs
- PIREPs
- ATC CDM (Collaborative Decision Making) briefings

Operational/Non-meteorological Variables

- Runway closures at airports
- Runway length at arrival and alternates
- Field conditions
- Contaminated runways
- Aircraft type
    - Example: Two-engine, smaller aircraft coming over the Rockies needs to be aware of mountainous terrain and check drift down alternates over the Rockies.
- Required Fuel for Situation
    - Based on both:
        - the meteorological conditions at arrival and departure airports
            - Aircraft must be able to handle unexpected delays due to weather.
        - legal landing weight
            - Aircraft cannot be overweight at landing.

Information from Person on Previous Shift

- Weather issues
- Operational issues

Appendix E: Reproduction of Online Questionnaire

Note: the questionnaire is presented here as it was presented online to respondents.

Display of Weather Information

PLEASE NOTE: Data from this survey are deidentified and thus not traceable to any pilot or pilot organization.

Click to Next Page

Display of Weather Information

Please answer the following questions regarding your flight experience. Do not use your browser's back button to return to the previous pages of this survey. Please use the back buttons provided at the bottom of each page.

1. Please indicate *all* FAR categories in which you operate.

- ☐ Part 91 VFR
- ☐ Part 91 IFR
- ☐ Part 135 VFR
- ☐ Part 135 IFR
- ☐ Part 121
- ☐ Other (please list)

2. If you operate in more than one category from above, please indicate the category in which you *most frequently* operate.

- ○ Part 91 VFR
- ○ Part 91 IFR
- ○ Part 135 VFR
- ○ Part 135 IFR
- ○ Part 121
- ○ Other

3. Please indicate *all* applicable FAA Certificates/Ratings.

- ☐ Private
- ☐ Commercial
- ☐ ATP
- ☐ Instrument
- ☐ CFI
- ☐ CFII
- ☐ Other

4. What is your current position on the flight deck?

- ○ Single Pilot
- ○ First Officer
- ○ Captain
- ○ Other

5. Please indicate your total flight time for each position below (hours).

Single Pilot

First Officer

Captain

Other

6. Please indicate *all* aircraft you operate.

- ☐ Piston single
- ☐ Piston twin
- ☐ Turboprop
- ☐ Commuter turboprop
- ☐ Light jet
- ☐ Medium jet
- ☐ Commercial jet
- ☐ Rotocraft

7. If you listed more than one aircraft above, now indicate the *primary* aircraft you operate (e.g., what type aircraft do you regulary fly for your occupation?)

- ○ Piston single
- ○ Piston twin
- ○ Turboprop
- ○ Commuter turboprop
- ○ Light jet
- ○ Medium jet
- ○ Commercial jet
- ○ Rotocraft

8. Do you primarily fly

- ○ passengers
- ○ freight

9. Do you have 'glass cockpit' experience?

- ○ Yes
- ○ No

10. Does your company have a policy regarding flight in and around weather?

- ○ Yes
- ○ No

11. Do you own a personal computer?

- ○ Yes
- ○ No

12. Approximately how many hours a week do you use a computer for activities other than email (e.g., games, writing, web-browsing)?

12 of 19 questions completed - please "click to next page" to continue.

Click to Go Back | Click to Next Page

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Display of Weather Information

In this survey, you will complete two parts.

Part 1
The first part of this survey includes 3 matrices that list weather phenomena and phases of flight.

We would like you to assess how important it is for a pilot to have access to information regarding various weather phenomena throughout a flight.

Part 2
The second part of this survey includes ***two videos*** with a general description of a Cockpit Situational Display being designed by the NASA Ames Flight Deck Display Research Laboratory. We would like you to view these videos and provide your opinions on the weather information.

Each video includes audio information. If you do not have audio set up on your computer, you may still view the videos. Just note that having both video and audio enhances the information.

Please "click to next page" to continue.

Click to Go Back | Click to Next Page

Display of Weather Information

When answering the questions within this part of the survey, please respond as if you are operating the aircraft you have indicated as your primary aircraft.

The matrices below list weather phenomena by row and phases of flight by column. As you consider each weather phenomenon, assume it exists along your flight path or in close proximity to your flight path. In moving through the matrix, **please rank how important it is for you to know about each weather phenomenon at each phase of flight.**

Please use the following ranking convention:
0 - The information is **not important** to the safety or efficieny of the flight. Knowing this information will not affect the flight for good or ill.
1 - It would be **nice to have** this information, but it is *not critical* to maintain flight safety.
2 - It is **critical for me to have** access to this information, as it will directly influence my ability to *maintain flight safety*.

Example:
In the column for "planning", rank how important it is to know about the current "cloud ceiling" by marking a 0, 1, or 2 in the matrix. As you continue to move through the matrix and come to "cruise" phase of flight, again, rank how important it is to know about the current "cloud ceiling." Please rank the importance of each weather phenomenon at each phase of flight.

13. Please complete the matrix below as instructed above.

	Planning	Departure	Cruise	Approach	Landing
Cloud ceiling					
Rain					
Freezing rain/sleet					
Hail					
Snow					
Present temperature					
Geographic temperature gradient					
Vertical temperature gradient					
Rate of temperature change					
Dewpoint					

14. Please complete the matrix below as instructed above.

	Planning	Departure	Cruise	Approach	Landing
Tornados					
Hurricanes					
Lightning					
Convection at departure alport					
Convection en route					
Convection at destination airport					
Haze					
Sand/dust storms					
Volcanic ash					
Static atmospheric pressure					
Rate of pressure change					

15. Please complete the matrix below as instructed above.

	Planning	Departure	Cruise	Approach	Landing
Ground wind direction					
Aloft wind direction					
Ground wind velocity					
Aloft wind velocity					
Clear air turbulence					
Gusts					
Mountain rotors					
Downdrafts					
Updrafts					
Jet stream					
Windshear					
Rate of pressure change					

Click to Go Back | Click to Next Page

Display of Weather Information

15 of 19 questions complete. Please "click to next page" to continue.

Click to Go Back | Click to Next Page

Display of Weather Information

This part of this survey includes two videos with a general description of a Cockpit Situational Display being designed by the NASA Ames Flight Deck Display Research Laboratory. We would like you to view these videos and provide your opinions on weather information.

The NASA Ames Flight Deck Display Research Laboratory has developed a Cockpit Situation Display.

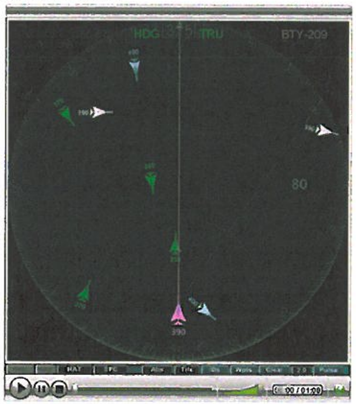
Please click the play button below to start animation and make sure that your speakers are on. Duration (0:01:08)

This video includes audio information. If you do not have audio set up on your computer, you may still view it. Just note that the information is enhanced by having both video and audio.

Please be patient as the video may take a moment to load.

To play the video please hit the play button located in the control panel immediately below the video.

The 3D Cockpit Situation Display



The NASA Ames Flight Deck Display Research Laboratory is **incorporating weather information** into the Cockpit Situation Display.

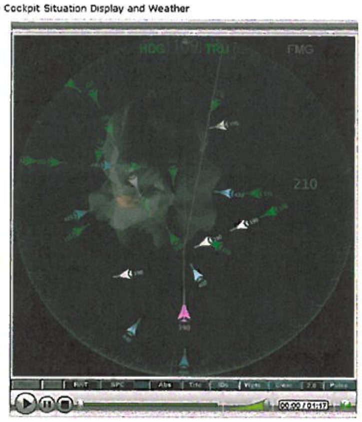
Please click the play button below to start animation and make sure that your speakers are on. Duration (0:01:17)

This video includes audio information. If you do not have audio set up on your computer, you may still view it. Just note that the information is enhanced by having both video and audio.

Please be patient as the video may take a moment to load.

To play the video please hit the play button located in the control panel immediately below the video.

The 3D Cockpit Situation Display and Weather



16. Were you able to listen to the audio narration during the videos above?

○ Yes

○ No

Click to Go Back | Click to Next Page

Display of Weather Information

We are soliciting feedback from pilots, such that we can provide weather information that will be optimal. Please help us in collecting such information.

We would like to know what additional types of weather information you believe would be useful, in general. Please answer the following questions to assist us in our efforts.

17. What **current** weather products do you believe might be useful if they were incorporated into this 3-dimensional display of airspace?

18. **Regardless of the weather products that are currently available,** what weather phenomena would you like to see represented on this 3-dimensional display of airspace? Please do not limit your answer by considering only current products here (e.g., if you want to see information about weather phenomenon X but it is currently impossible to receive such information or if it would require integrating several of the current products, we want to know about it!).

19. Please provide any questions or comments about this survey and its contents.

You are done!!!! Please "click to next page" to complete the questionnaire.

Click to Go Back | Finished? Submit your Survey

Display of Weather Information

Thank you for taking our survey. Your response is very important to us.

Appendix F: Preliminary Responses to Primary Survey Questions

Note: Percentage represents the number of respondents (out of approximately 12 respondents) that rated a particular weather phenomenon as being a "2" (critical) on the following scale:

0 The information is **not important** to the safety or efficiency of the flight. Knowing this information will not affect the flight for good or ill.
1 It would be **nice to have** this information, but it is *not critical* to maintain flight safety.
2 It is **critical for me to have** access to this information, as it will directly influence my ability to *maintain flight safety*.

Note: Black, bolded boxes represent any cell that yielded a response greater than 70%.

Phase of Flight

Weather Phenomena	Planning	Departure	Cruise	Approach	Landing
Cloud ceiling	55%	55%	9%	64%	***82%***
Rain	36%	36%	9%	46%	64%
Freezing rain/sleet	***100%***	***91%***	*73%*	***91%***	***100%***
Hail	***82%***	***91%***	*73%*	***91%***	***100%***
Snow	55%	46%	9%	36%	***91%***
Present temperature	55%	46%	9%	46%	55%
Geographic temperature gradient	18%	0%	0%	0%	0%
Vertical temperature gradient	27%	18%	9%	9%	0%
Rate of temperature change	36%	9%	0%	9%	9%
Dewpoint	27%	36%	9%	36%	46%
Tornados	***100%***	***100%***	46%	***91%***	***100%***
Hurricanes	***91%***	***82%***	55%	***82%***	***82%***
Lightning	55%	***91%***	*73%*	***82%***	***100%***
Convection at departure airport	*73%*	***82%***	0%	9%	18%
Convection enroute	64%	27%	64%	9%	0%
Convection at destination airport	***82%***	9%	36%	***91%***	***82%***
Haze	9%	18%	0%	27%	36%
Sand/dust storms	***82%***	*73%*	27%	*73%*	*73%*
Volcanic ash	***91%***	***91%***	***91%***	***91%***	***82%***
Static atmospheric pressure	27%	27%	0%	36%	46%
Rate of pressure change	46%	9%	9%	27%	18%
Ground wind direction	55%	*73%*	9%	55%	***91%***
Aloft wind direction	64%	9%	*73%*	*73%*	9%
Ground wind velocity	*73%*	***82%***	9%	36%	***91%***
Aloft wind velocity	*73%*	9%	*73%*	18%	18%
Clear air turbulence	*73%*	55%	***82%***	46%	46%
Gusts	55%	***82%***	0%	46%	***91%***
Mountain rotors	***82%***	*73%*	***91%***	64%	64%
Downdrafts	46%	*73%*	55%	*73%*	***82%***
Updrafts	46%	64%	36%	55%	*73%*
Jet stream	*73%*	9%	64%	0%	0%
Windshear	***82%***	***91%***	46%	***82%***	***91%***
Rate of pressure change	36%	18%	9%	9%	27%