HUMAN-CENTERED SYSTEMS ANALYSIS OF AIRCRAFT SEPARATION FROM ADVERSE WEATHER

BY

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S.M., AERONAUTICS AND ASTRONAUTICS, MASSACHUSETTS INSTITUTE OF TECHNOLOGY, 2000

SUBMITTED TO THE DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY IN AERONAUTICS AND ASTRONAUTICS AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2004

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Abstract

Adverse weather significantly impacts the safety and efficiency of flight operations. Weather information plays a key role in mitigating the impact of adverse weather on flight operations by supporting air transportation decision-makers' awareness of operational and mission risks. The emergence of new technologies for the surveillance, modeling, dissemination and presentation of information provides opportunities for improving both weather information and user decision-making. In order to support the development of new weather information systems, it is important to understand this complex problem thoroughly.

This thesis applies a human-centered systems engineering approach to study the problem of separating aircraft from adverse weather. The approach explicitly considers the role of the human operator as part of the larger operational system. A series of models describing the interaction of the key elements of the adverse aircraft-weather encounter problem and a framework that characterizes users' temporal decision-making were developed. Another framework that better matches pilots' perspectives compared to traditional forecast verification methods articulated the value of forecast valid time according to a space-time reference frame. The models and frameworks were validated using focused interviews with ten national subject matter experts in aviation meteorology or flight operations. The experts unanimously supported the general structure of the models and made suggestions on clarifications and refinements which were integrated in the final models.

In addition, a cognitive walk-through of three adverse aircraft-weather encounters was conducted to provide an experiential perspective on the aviation weather problem. The scenarios were chosen to represent three of the most significant aviation weather hazards: icing, convective weather and low ceilings and visibility. They were built on actual meteorological information and the missions and pilot decisions were synthesized to investigate important weather encounter events. The cognitive walk-through and the models were then used to identify opportunities for improving weather information and training. Of these, the most significant include opportunities to address users' four-dimensional trajectory-centric perspectives and opportunities to improve the ability of pilots to make contingency plans when dealing with stochastic information.

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ACKNOWLEDGEMENTS

I wholeheartedly wish to thank my thesis advisor, John Hansman, for providing me with continuous expert guidance throughout the course of my research journey. I also wish to thank Professors Jim Kuchar and Nancy Leveson for their constructive feedback throughout the years. Thanks also go to four readers whose insights made this thesis stronger, including Drs. Tom Reynolds, Steven Bussolari, William Hall and Captain Alan Midkiff.

Sincere thanks to Drs. Andrew Reehorst and Thomas Bond from the NASA Glenn Research Center for their support. This work was supported by the National Aeronautics and Space Administration Glenn Research Center under grant NAG3-2178, by the Natural Sciences and Engineering Research Council of Canada, the *Fonds Québécois de Recherche sur la Nature et les Technologies* (previously the Fonds pour la formation de chercheurs et l'aide à la recherche of Québec) and Zonta International.

Sincere thanks go to the ten national subject matter experts that I interviewed over the summer of 2003 for contributing their time, opinions, recommendations and encouragement in my research endeavour. Their help served to validate and improve the models of Chapter Three. Their names are kept anonymous for research reasons. Thanks are extended to AOPA, Meteorlogix, NASA, NWS, MIT Lincoln Laboratory, Alan Midkiff and William Hall for permission to reproduce pictures included herein.

Thanks also go to several people who facilitated my site visits and, in some cases, my participation in activities that helped me learn more about how elements of the current and future weather information system are generated, distributed, regulated, used, operated and researched. These include Mark Spatz at Air Cargo Express, Mooly Dinnar and Simon Matthews at Avidyne, Jim Evans, Dale Rhoda and Rich DeLaura at the MIT Lincoln Laboratory, Marcia Politovitch and Bruce Carmichael at NCAR, Bucch Griffin at the Bridgeport Flight Service Station, William Babcock at the Taunton National Weather Service, Maria Pirone at WSI, Daniel Chrétien at Environnement Canada, Marc Lussier at NavCanada and Jack Howell at ICAO.

I wish to thank my numerous colleagues at MIT for feedback on my research and for their much appreciated collaboration and friendship throughout the years, including Francis, Jonathan, Hayley, Laura, Roland, Phillippe, Lee, Georg, Miguel, Simon, Xue'en, Katherine and many more. Sincere thanks go to my dear family, including Charles, Nicole, Pierre-André, Suzanne, Patricia. Finally, the deepest thanks go to Bill for support, love and inspiration!

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ACRONYMS

3-D	Three-Dimensional
4-D	Four-Dimensional
AIAA	American Institute of Aeronautics and Astronautics
ADDS	Aviation Digital Data Service
AIM	Airmen Information Manual
AIRMET	Airman's Meteorological Advisory
AMS	American Meteorological Society
AOC	Airline Operation Center
AOPA	Aircraft Owners and Pilot Association
ASR	Airport Surveillance Radar
ATC	Air Traffic Control
ATM	Air Traffic Management
ATIS	Airport Terminal Information Service
AWC	Aviation Weather Center
BLW	Below
BR	Mist
BTN	Between
BYD	Beyond
CCFP	Collaborative Convective Forecast Product
CD	Correct Detection
CIP	Current Icing Potential
CNS	Communication, Navigation and Surveillance
CONTG	Continuing
CSI	Critical Success Index
CR	Correct Rejection
DSD	Droplet Size Distribution
DoT	Department of Transport
DUAT	Direct User Access Terminal
EDT	Eastern Daylight Savings Time
EMC	Environment Modeling Center
ERN	Eastern
EST	Eastern Standard Time
EWD	Eastward
FA	Area Forecast
FA	False Alarm
FAA	Federal Aviation Administration
FAR	False Alarm Ratio
FAR	Federal Aviation Regulation
FBO	Fixed Based Operator
FD	Winds Aloft Forecast
FIS-B	Flight Information Service Broadcast
FL	Flight Level
FM	From
FSL	Forecast Systems Laboratory
FSS	Flight Service Station
FRZLVL	Freezing Level
GA	General Aviation
GASA	Geographic Area Safe Altitude
hrs	Hours
ICAO	International Civil Aviation Organization
ICGICIP	Icing in Clouds and in Precipitations
IMC	Instrument Meteorological Conditions
IFR	Instrument Flight Rules
ITWS	Integrated Terminal Weather System
KALB	Albany Airport, New York
KBOS	Boston Logan International Airport, Massachusetts
KCLE	Cleveland Hopkins International Airport, Ohio
KCGF	Cuyahoga County Airport, Ohio
KELM	Elmira/Corning International Airport, New York
KFLL	Fort Lauderdale Airport, Florida
KFPR	Fort Pierce Airport, Florida
KJAX	Jacksonville Airport, Florida
KMEM	Memphis Airport, Tennessee
KMSY	New Orleans International Airport, Louisiana
KOWD	Norwood Memorial Airport, Massachusetts
kt	Knot
LE	Lake Erie
LIFR	Low IFR
LWC	Liquid Water Content
LO	Lake Ontario
MD	Missed Detection
MEA	Minimum Enroute Altitude
MEF	Maximum Elevation Figure
METAR	Aviation Routine Weather Report

MD	Missed Detection
MVFR	Marginal VFR
MSE	Mean Square Error
MULT	Multiple
MXD	Mixed
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Center for Environmental Predictions
NEXRAD	Next Generation Radar
nm	Nautical Miles
NRC	National Research Council (U.S.)
NRN	Northern
NOAA	National Oceanic and Atmospheric Administration
NTSB	National Transportation Safety Board (U.S.)
NWS	National Weather Service
OAG	Official Airline Guide
OCNL	Occasional
OROCA	Off Route Obstruction Clearance Altitude
OVC	Overcast
PC	Personal Computer
PDA	Personal Digital Assistant
PIREP	Pilot Weather Report
PROB	Probability
RA	Rain
-RA	Light Rain
-RASN	Light Rain and Snow
RAP	Research Application Program
RAPT	Route Availability Planning Tool
RVR	Runway Visual Range
RTVS	Real-Time Verification System
SCT	Scattered
SDTFAR	Signal Detection Theory False Alarm Rate
SID	Standard Instrument Departure Procedure
SIGMET	Significant Meteorological Information
SME	Subject Matter Expert
SN	Snow
SPECI	Special Observation
SPRDG	Spreading
sm	Statute Mile
STAR	Standard Terminal Arrival Procedure
SUA	Special Use Airspace
TAF	Terminal Forecast
TDWR	Terminal Doppler Weather Radar
TMC	Traffic Management Center
TMU	Traffic Management Unit
TSRA	Thunderstorms and Rain
TSS	True Skill Score
UPDT	Update
VHF	Very High Frequency
VFR	Visual Flight Rules
VIP	Video Integrator and Processor
VOR	VHF Omni-directional Range
WMM	Weather Mental Model
WMO	World Meteorological Organization
Wx	Weather
Z	Zulu

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1 INTRODUCTION

Adverse weather remains one of the leading causes of aviation accidents and a primary factor responsible for reduced capacity in the air transportation system. Weather information plays a paramount role in mitigating the safety impact of adverse weather by helping air transportation decision-makers avoid potentially hazardous meteorological conditions. Weather information can also improve the efficiency of aviation operations by supporting enhanced planning.

Recognizing the role of weather information, several national and international efforts are under way to develop and/or improve various components of the weather information system. These efforts target key areas of research and development needs and include NASA's Aviation Safety Program, the FAA's Aviation Weather Research Program, Environment Canada's participation in the international Alliance Icing Research Study, the collaborative activities of Météo-France and the Centre National de Recherche Météorologique, the United Kingdom's Meteorological Office Aviation-Related Research Program, the work of the Meteorology Section of ICAO's Air Navigation Bureau and the Aeronautical Meteorology Programme of the World Meteorological Organization (WMO). In recent years, a variety of commercial providers has filled the avionics market with new cockpit weather datalink capability. It appears that most weather products up-linked to the cockpit had previously been developed for ground-based applications and it is not clear that these products capture pilots' cockpit-based weather information needs.

The main objective of this thesis is to explore and explain how existing and prospective elements of the weather information system help support human decision-making and avoidance of adverse weather regions. The weather information products encompassed by the scope of this analysis include a variety of ground-based and airborne systems, including cockpit weather datalink products. A human-centered systems approach is applied to this analysis in order to consider the human as part of the larger air transportation and weather information system.

Focusing on adverse weather avoidance as a key mitigation strategy, the analysis encompasses mainly three types of weather phenomena: convective weather, icing and restricted ceilings and visibility. The impact of these weather phenomena on flight operations is reviewed in Section 1.1. It is observed that, from the perspective of pilots, the tasks of keeping aircraft from flying into adverse weather conditions such as turbulence and icing feature similarities with the tasks of traffic and terrain avoidance. The

discussion of the differences and similarities between weather phenomena and other external hazards is included in the analysis and provided in more detail in Appendix B. Section 1.2 establishes the scope of the thesis and Section 1.3 presents an outline of the thesis.

1.1 SAFETY AND EFFICIENCY IMPACT OF ADVERSE WEATHER ON AIR TRANSPORT OPERATIONS

Aviation is a safe means of transportation in absolute terms, with a death risk per flight on first-world domestic flights of 1 in 13 million (Barnett, 2001). However, in order for air transportation to keep growing safely and efficiently, it is important to address the continuing issues that challenge its operations. Adverse weather is one of the key factors that impact the safety and efficiency of flight operations and it can be mitigated with better information.

In order to evaluate the safety impact, an analysis of weather-related accident statistics was conducted using the most recent 10-year data available from the National Transportation Safety Board (2000, 2002). Statistical data was calculated for four categories of operation: Part 121, Scheduled Part 135, Non-Scheduled Part 135, and General Aviation. Part 121 applies to air carriers, such as major airlines and cargo haulers that fly large transport aircraft. Part 135 applies to commercial air carriers commonly referred to as commuter airlines and air taxis. Data for Scheduled and Non-Scheduled operations under Part 135 is shown separately. General Aviation refers to most of the remainder of civilian flight operations.

As can be seen in Figure 1.1, non-scheduled operations, such as General Aviation and Non-Scheduled Part 135, experience significantly higher accidents. As can be seen in Figure 1.12 however, the ratio of weather-related accidents is fairly uniform across the types of flight operations and accounts for nearly one-quarter (23.4%) of all aircraft accidents. The proportion of fatal accidents that have weather as a contributing factor is even higher and accounts for nearly one-third of fatal accidents (30.7%).

In absolute terms, there was an annual average of 537 weather-related accidents over that period, and an annual average of one weather-related accident every 16 hours of U.S. National Airspace System (NAS) operation[1]. Major Air Carrier operations have a higher safety level, but still include an average of one

[1] *Assuming uniform operation throughout 365 days*

weather-related accident of US-registered aircraft every 49 days. More detailed statistics are also provided in Appendix A.

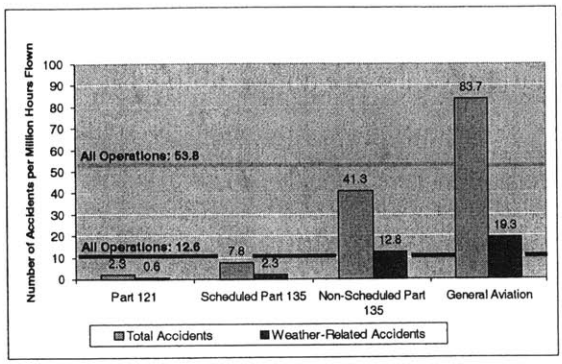

Figure 1.1: Average annual U.S. accident rate statistics[2]

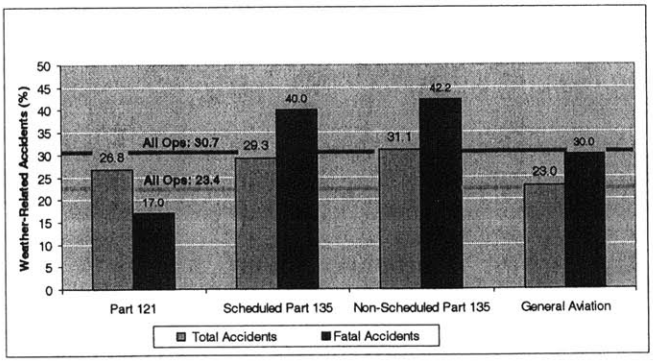

Figure 1.2: Average U.S. weather-related accident statistics

In addition to safety implications, weather has a major impact on the economics of air transportation. Weather annually costs an estimated $3 billion to the U.S. airline industry (Office of the Federal Coordinator for Meteorology, 1999) including expenses related to accident damage and injuries, delays and unexpected operating costs. Estimates for the share of weather delays that are avoidable have been estimated to be about 40%, and the cost of convective weather delays that are avoidable to over $300 million dollars (Evans, 2004). Moreover, annually, an average of 66% of departure and en-route delays, equivalent to about 200,000 delays, is attributed to weather (U.S. Department of Transportation, 1986-1997).

Weather also affects aviation operations in significant ways that are difficult to quantify or trace, but that are nevertheless worth mentioning. They include passenger delay, discomfort and inconvenience; air traffic controller workload; airline schedule disruptions, accident liability; labor contentions; limited military readiness and lower strategic advantage; environmental impact of extra fuel burn; public perception of air transportation risk.

[2] *Based on data for the period 1987-1996*

1.2 SCOPE OF THE THESIS

This section provides a synopsis of the scope of the human-controlled adverse aircraft-weather encounter problem treated in this thesis. It sets the context and provides clarifications with regard to what is and is not included in the thesis in relation to the type of adverse weather mitigation strategy studied, the weather phenomena considered and the air transportation decision-makers affected.

The Case for Weather Avoidance

A key strategy to mitigate the impact of adverse weather on the safety and efficiency of air transport operations is to provide weather information that supports better decision-making. Another strategy is to enhance the tolerance of aircraft to their environment, which is not treated in the thesis. This second strategy has achieved great improvements in the ability of some aircraft to operate under restricted ceilings and visibility, and of other aircraft to be better protected against icing conditions. However, for the foreseeable future, engineering solutions are unlikely to produce a cost effective all-weather aircraft. Improvements in the tolerance of aircraft to icing and other adverse weather conditions is likely to simply shift the intensity or type of adverse weather conditions about which aviation users need to be informed.

Relevant Weather Phenomena

For a class of adverse aircraft-weather encounter problems, the most desirable operational risk mitigation strategy consists of having aircraft avoid the areas where the weather conditions are present altogether. The weather phenomena associated with the most significant impact on aviation operations include icing, convective weather, restricted ceilings and visibilities and non-convective turbulence. In each case, adverse weather regions that are spatially distributed and temporally varying may be identifiable. The definition of the boundaries of adverse weather regions is dependent on factors such as aircraft type, equipage, certification and pilot qualifications.

Key Air Transportation Decision-Makers

Users of weather information who have an impact on the decisions made with regard to air transportation operations principally include pilots, air traffic controllers and airline dispatchers. The thesis work is mainly focused on pilot decision-making but, where appropriate, analyses are extended to include the perspectives of air traffic controllers and airline dispatchers.

1.3 THESIS OUTLINE

This thesis is organized in six chapters. Chapter Two provides a background on why specific weather phenomena are of concern for flight operations and discusses recent developments in research related to aviation weather information system elements such as surveillance, forecasting, dissemination, presentation, information needs and information products.

Chapter Three presents the modeling part of the work presented in the human-centered systems analysis. A high-level model decomposition is presented that serves as an overview of the more detailed models of the physical situation dynamics, the information system architecture and the model of pilots' cognitive processes. In order to provide a structure for explaining the role of a key dimension in weather-related decision-making, the role of time, a framework of temporal decision-making is developed. One of the building blocks of the framework is a model of pilots' cognitive weather projection. Also, the limitations between pilots' perception of forecast accuracy and the traditional methods for assessing forecast goodness are identified. In response, a framework that captures pilots' spatio-temporal trajectory-centric perspective is developed to serve as a basis to assess the value of weather forecasts. The results show the influence of forecast temporal and spatial resolution on forecast value. The model development and validation processes are also explained.

Chapter Four presents a cognitive walk-through of three adverse aircraft-weather encounter scenarios. These scenarios serve to explore pilot decision-making and information use in the context of specific weather-intensive scenarios. Actual weather information was recorded for these scenario studies and the mission and pilot decision were synthesized to represent difficult characteristic features of weather encounters.

Chapter Five discusses the key implications emerging from the descriptive models and from the scenario-based analysis and identifies insights that have implications for weather information. The chapter is organized in terms of general recommendations, implications for the development of specific weather information products and for training and implications that are weather-specific.

Finally, Chapter Six summarizes the key results and recommendations emerging from the thesis and identifies opportunities for future work.

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2 BACKGROUND AND LITERATURE REVIEW

2.1 INTRODUCTION

Two main factors have been triggered interest in research related to the topics of aviation weather information and decision-making. The first factor has been the realization that weather has a significant impact on aviation safety and efficiency. Section 2.1 provides background on this topic. The second factor is the advent of new technology and methods for improving weather information. Section 2.2 provides an overview of the technology and research efforts related to weather surveillance, forecasting, dissemination, information presentation and information needs. A variety of weather information products are available to pilots and the main products are presented in Section 2.3. Finally, Section 2.4 provides conclusions for the chapter.

2.2 BACKGROUND ON ADVERSE WEATHER PHENOMENA

Adverse weather impacts aviation operations in terms of safety and efficiency. Four of the most important weather phenomena impacting aviation operations are discussed in this section: icing, convective weather, non-convective turbulence and restricted ceilings and visibilities. The reasons for concern and mitigation strategies employed in operations are described for each type of weather conditions.

2.2.1 Icing

Aircraft flight through icing conditions lead to the accretion of ice layers on exposed surfaces. Ice accretion on winds, vertical and horizontal stabilizers and propeller blades may dramatically affect the performance, stability and control of aircraft, by reducing lift, increasing drag and weight, reducing thrust and leading in the worse cases to aircraft stall, loss of control and ultimately incidents and accidents. In jet aircraft operations, chunks of ice breaking loose from the aircraft surfaces can be ingested into the engine, causing damage to compressor blades and affecting the performance of the engines.

There are essentially two methods for mitigating the impact of adverse icing conditions on flight operations. The first one involves improving the tolerance of aircraft to adverse icing conditions, and the second involves separating aircraft from adverse icing conditions. The intensity of conditions adverse to aircraft operations is highly dependent on specific aircraft characteristics, but there are icing conditions that are adverse to all aircraft operations. Therefore, the characteristics and level of ice protection of aircraft only shifts the boundaries and types of icing conditions that are hazardous.

The severity of aircraft icing is defined in the Airmen Information Manual (2003) according to the influence of the rate of ice accumulation on the level of hazard to the flight operation on a four-point scale, including trace, light, moderate and severe. Using this classification, the Federal Aviation Regulations (FARs) stipulate what icing severity levels should be avoided as a function of whether aircraft are certified for flight into know icing and according to the aircraft equipment and the type of flight operations.

2.2.2 Convective Weather

Convective weather, including thunderstorms, is dangerous to flight operations due to the severity and the diversity of the weather phenomena that may be associated with it. The list of adverse phenomena that may be present inside or in the vicinity of a thunderstorm cell includes turbulence, icing, hail, lightning, tornadoes, gusty surface winds, low-level wind shear, adverse effects on the altimeter, and restricted ceilings and visibilities. The effect of turbulence and restricted ceilings and visibilities are explained in the two next subsections in details. To touch on the effect of other phenomena, hail has been observed to seriously affect the skin of aircraft, affecting airflow and causing a need for expensive aircraft repair, as well as the structural integrity of engine blades. Lightning can lead to electric surges and cause instrument failures. Tornadoes can lead to accidents due to aircraft loss of control. Low level wind shear has caused several accidents in the past by leading aircraft to fly in the ground due to significant loss of performance.

The Airmen Information Manual recommends that pilots avoid thunderstorms that give an intense radar echo by at least 20 miles laterally, and to clear the top of a known or suspected severe thunderstorm by at least 1,000 feet altitude for each 10 knots of wind speed at the cloud top (FAA, 2003, 1-1-26).

2.2.3 Non-Convective Turbulence

The Glossary of Meteorology (2000) defines aircraft turbulence as "irregular motion of an aircraft in flight, especially characterized by rapid up-and-down motion, caused by a rapid variation of atmospheric wind velocities. This can occur in cloudy areas (particularly inside or in the vicinity of thunderstorms) and in clear air".

At lower intensities, the rapid and erratic accelerations induced by turbulence may cause dislocation of objects and passengers within the aircraft cabin, resulting in serious passenger injuries. Stronger random oscillations forced on the aircraft and its structural members may result in high stresses, metal fatigue, and even lead to rupture and structural failure of aircraft in flight. Finally, turbulence may excite strong rigid dynamic modes which can lead to difficulties in controlling aircraft, or even loss or control and consequent accidents (Mahapatra, 1999)

Pilots may avoid areas of turbulence altogether when it is known to them, based on weather forecasts as well as pilot weather reports. If penetration is inevitable due to lack of sufficient warning in order to request a different altitude, pilots reduce aircraft speed to a turbulence penetration speed/Mach number that will reduce the stress on the aircraft and potentially the discomfort in the cabin. In addition, pilots of passenger aircraft will also share the information with and influence the operations in the cabin, leading to passengers being requested to be seated, food carts to be put away and possibly that all flight attendants to be seated.

Similarly to icing conditions, the level of hazard of turbulence is rated in the operational context according to the severity of encounters of aircraft with turbulence conditions. Appendix Table E provides an overview of the severity levels used, including light, moderate, severe or extreme turbulence.

Various government organizations including NCAR, the FAA and ICAO are working on ways to improve on the current hazard index by shifting towards objective and aircraft-independent metrics.

2.2.4 Restricted Ceilings and Visibilities

For pilots who are not qualified for flight into instrument meteorological conditions (IMC), exposure to the conditions may lead them to lose control of their aircraft due to spatial disorientation and collide with the terrain. Pilots trained for instrument flight who operate aircraft that are equipped and certified for

flight into IMC may operate safely in conditions of restricted ceilings and visibilities. Pilots who are not adequately trained should avoid conditions of restricted ceilings and visibilities.

Restricted ceilings and visibilities also have another important efficiency-related impact on aviation operations. When the ceilings and visibility at airports are insufficient for flight under Visual Flight Rules (VFR), the separation between aircraft used in ATC operations increases drastically. Under VFR operations, the separation between aircraft is often left to the discretion of the pilots based on visual identification. Under Marginal (MVFR) and IFR conditions, Air Traffic Controllers use time intervals and distances between aircraft that are much larger than under VFR. In addition, flight operations into closely-spaced parallel runways also use greater spacing between aircraft when the conditions are not VFR. Although these conditions affect the efficiency of flight operations, they are not included in the scope of this thesis because they do not constitute adverse weather that should be avoided.

2.3 LITERATURE REVIEW

Various approaches to improving weather information have focused on the key components of weather information systems, including weather surveillance, weather modelling and dissemination, information dissemination and presentation as well as weather information needs of the users. This section reviews the latest development and the key issues encountered in relation to each of these systems.

2.3.1 Weather Surveillance

Efforts have continually been applied to the development of new instrumentation and sensors for *in situ* measurement and remote sensing of adverse weather conditions. The technology to survey regions of convective weather and restricted ceilings and visibilities is much more mature than the latest technology to detect adverse icing and adverse turbulence regions.

Sensors used for the surveillance of convective weather have been operational for several years and include radar such as the WSR-88D (NEXRAD) system which consists of about 150 nearly identical radars deployed over the United States in the 1990s (NRC, 2002). Data from NEXRAD is used to generate regional and national mosaics. Other operational radars include the Terminal Doppler Weather Radar (TDWR) which is used in the vicinity of airports. Radar used for the surveillance of traffic, such as the ASR-9 and ASR-11, also detect some features of convective weather. The surveillance of low-level

wind shear is also commonly performed in the vicinity of airports via the Low Level Wind shear Alerting System (LLWAS). In addition, most commercial aviation airplanes are equipped with airborne weather radars that detect convective weather and wind shear regions ahead of them.

Ceilings and visibility (or runway visual range, RVR) are routinely measured at most airports around the United States and at major airports around the world. Satellite observations provide additional information about cloud tops and coverage between measuring stations.

In relation to turbulence, new sensors and radar algorithms are being investigated for remotely detecting hazardous turbulence conditions in the atmosphere. However, the technology development requires further work before becoming operational (Cornman et al., 2002). With regard to icing, the most recent developments have tackled the challenging problem of the remote sensing of various surrogate variables. Equipment including radiometers, radio acoustic sounding systems, lidar and radar have been tested in ground-based and airborne platforms (Reehorst, 2003; Ryerson et al., 2002; Reinking et al, 2000; Williams et al., 2002). Satellite-based remote sensing of icing conditions is also being investigated (Minnis et al., 2003).

2.3.2 Weather Modelling and Forecasting

Numerical weather models constitute the main source of information from which public and aviation weather forecasts are generated. In the United States, they are prepared by the Environment Modeling Center (EMC) of the National Weather Service's (NWS) National Center for Environmental Prediction (NCEP). The state of the art in weather forecasting involves the deployment over the last decade of numerical gridded weather forecasts such as the Rapid Update Cycle (RUC) that cover the domestic United States. The latest version of the forecast has a 20-kilometer horizontal resolution (and is called the RUC20) and entered operation in 2002. It produces short-range and 12-hour forecasts at regular time intervals by integrating data from a variety of sources including the GOES satellite, radiosondes, rawindsondes and radar (Benjamin et al., 2002). It incorporates high-resolution gridded data from land-use and soil-type information, runs several diagnostic algorithms applied to microphysics modelling and convective parametrization, and outputs information usable by aviation weather forecasters including visibility, temperature, dewpoint, winds and precipitation (Benjamin et al., 2002).

With regard to convective weather, the Integrated Terminal Weather System (ITWS) integrates data from a series of sensors, incorporates a suite of weather prediction algorithms and provides information

products to air traffic personnel and airlines. ITWS was developed by the MIT Lincoln Laboratory and manufactured by Raytheon. The current version provides nowcast and short-term predictions of convective weather over a 20-minute forecast horizon.

Tremendous development has also been witnessed in relation to the verification, or quality assurance, of weather forecast products. Historically, as new weather information products emerged and came into operational use, their quality was tested through controlled studies on a sample of the data which was manually and subjectively analyzed. The development of the Real-Time Verification System (RTVS) has changed all that by providing consistent, unbiased and objective verification statistics computed in near real-time and emphasizing forecasts critical to aviation (Mahoney et al., 2002). The RTVS algorithms mainly compare forecasts with observations using a statistical framework for verification developed by Murphy and Winkler (1987) on a volumetric grid basis. In each case, the forecasts and observations are treated dichotomously (yes/no) by applying thresholds to the data, and a computation of the statistics is then based on a standard two-by-two contingency table, such as the one shown in Table 2.1 (Brown et al., 1997). Such contingency table compares in a dichotomous manner forecasts and observations.

Table 2.1: Standard two-by-two contingency table for forecast verification

		Forecast	
		Yes	**No**
Observation	**Yes**	Correct Detection	Missed Detection
	No	False Alarm	Correct Rejection

2.3.3 Weather Information Dissemination

Weather datalink technology has revolutionized the weather information available in the cockpit over the past few years. Now, pilots may view color graphical images of weather in near real-time in their cockpits at prices that are becoming affordable to most. A tremendous variety of infrastructures, service providers and display options have emerged in the last few years for providing weather information to the cockpit. The communication infrastructure includes geostationary and low earth orbit satellites as well as cellular and other weather-datalink dedicated ground networks.

The infrastructure behind weather datalink can be broken down into five components, some of which are illustrated in Figure 2.1 (AOPA, 2004):

1) Weather information provider to be provided as the content of the message; examples of industry players include WSI, Meteorlogix and the National Weather Service;

2) A weather datalink service provider that bundles the weather information and sends it out either as broadcast or on a request/reply basis; examples of industry players include AnywhereWx, WxWorx, Echo Flight, Arnav, Aircell, Avidyne, WSI;

3) A communication service provider, either ground-based or satellite-based, as shown in Figure 2.1; examples of industry players include Aircell, GlobalStar, XM Radio, the FAA-industry FIS-B, WSI, Orbcomm;

4) A receiver or transceiver box that collects the data on-board the aircraft, as shown in Figure 2.1; examples of industry players include RCOM, Heads Up Technologies, WSI, Aircell, Avidyne, GlobalStar, Echo Flight, Honeywell;

5) A display device, either portable or panel-mounted, as shown in Figure 2.1. Examples of industry players include: avionics manufacturers (e.g., Avidyne, Garmin, Arnav, Rockwell Collins, Honeywell, L-3 Avionics, Chelton and Universal Avionics); manufacturers of various portable platforms such as electronic flight bags (e.g., Advanced Data Research, CMC Electronics, Paperless Cockpit, AirGator and Echo Flight), tablet computers (e.g., Fujitsu), PC laptops and personal digital assistants.

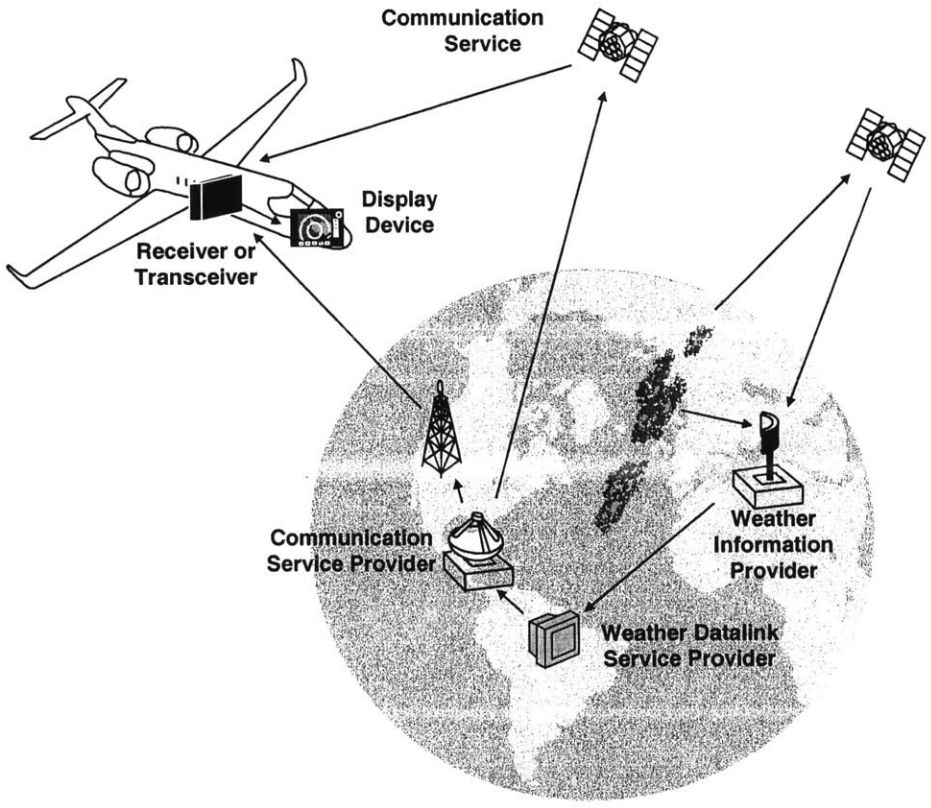

Figure 2.1: Some elements of the weather datalink infrastructure

Most weather datalink providers supply the same weather information, including the National Weather Service basic products and NEXRAD images. The main differences are found in relation to the frame of the representation (i.e., North-up versus track-up), whether the weather information is integrated with navigation information (e.g., maps), the spatial resolution of the weather information (ranging from 2 km-grid to dozens of nautical miles), the coverage of the data link service (limited at low altitudes for ground-based services) and the presentation and colouring of the weather images, as discussed in the next section.

2.3.4 Weather Information Presentation

The presentation of weather information has been investigated through experiments, surveys, interviews with pilots as well as through the use of experimental products by aviation users. Studies of the influence of generic weather representation features have identified the benefits of graphical over aural weather information (Wickens, 1984; Latorella and Chamberlain, 2001) and the ambiguity limitations of three-dimensional weather displays (Boyer & Wickens, 1994)). Another study found that, without ownship position in a graphical weather display, pilots did not make better diversion decisions than without the graphical weather information (Yucknovicz et al., 2000).

Variables measured in these studies include subjective ratings such as information sufficiency scores, confidence ratings, ratings of perceived performance (Latorella and Chamberlain, 2001) and perceived hazard level (Lind et al., 1995), all of which have limitations related to the biases of pilots' perception. Objective measures have been investigated and include general awareness (Potter et al., 1989), decision quality with regard to route selection (Vigeant-Langlois & Hansman, 2000), percentage of correct decisions (Wanke et al., 1990; Wanke & Hansman, 1992) and weather-related communication frequency (Lind et al., 1995).

2.3.5 Weather Information Needs

The information needs of aviation weather information users have been studied in various efforts in a general way as well as in relation to specific weather information products. A recent book published by the National Research Council (NRC) summarized the results of a workshop investigating the needs of the operational community of convective weather forecast products (NRC, 2003). Information needs to address air traffic delays by the community that influences traffic flow in the Air Traffic Management (ATM) system and ways to move forward and improve on the current weather information products were identified. These included the identification of critical tasks such as the determination of the means for

generating and applying probabilistic forecasts in ATM and clarifying concepts relevant to the assessment of forecasts.

A study at the MIT Lincoln Laboratory analyzed convective weather information users' tasks and subjective information needs and found that different users perceived that they needed different combinations of trade-offs between forecast accuracy and lead times. For example, airline dispatchers and Traffic Management Units (TMUs) of Air Route Traffic Control Center were interested in greater lead times compared to pilots and Traffic Management Center users despite lower accuracies for tasks having long range implications (Forman et al., 1999).

A study conducted by Georgia Tech provides a list of requirements for weather information (Keel et al., 2000), although most of them are statements about how to improve weather information that do not meet basic characteristics of good requirements (Kar et al., 1996). For example, they do not provide statements about necessary qualities of information systems, and most importantly they are not verifiable through any of the traditional methods such as inspection, analysis, demonstration or test.

With regard to training, Wiggins and O'Hare have found through computer-based studies that training pilots to better evaluate the cues related to deteriorating ceilings and visibilities improved the timeliness of weather-related decision-making (Wiggins and O'Hare, 2003).

2.4 BACKGROUND ON WEATHER INFORMATION AND DECISION-SUPPORT TOOLS

A variety of weather information tools have been developed for pilots, air traffic controllers and airline dispatchers. A few key weather information products are reviewed in this section to illustrate the scope and underlying infrastructure of these products and because some of them are used in the later sections of the thesis. The review focuses on the information tools that are used in the scenario-based cognitive walk-through of Chapter Four and include briefings (the DUAT), selected value-added information tools available publicly (ADDS) or through membership (AOPA-Meteorlogix), and a product used by ATC and airline dispatchers to collaborate on weather decision-making (the CCFP).

2.4.1 The Direct User Access Terminal

The Direct User Access Terminal (DUAT) is a service available on the worldwide web (*www.duat.com* and *www.duast.com*) or via telnet. It enables pilots to obtain a standard weather briefing in textual form using their personal computer. It constitutes an alternative to the use of the phone to obtain a standard weather briefing. The standard weather briefing products are in textual form and include a variety of weather reports and forecast products for the relevant planned flight time period.

An example one of the multiple textual forecasts provided through DUATS in un-decoded format is illustrated in Insert 2.1. In this case, the TAF is provided for Boston airport (KBOS) on the 10th of the month at 18 hours and 8 minutes of GMT time (as shown by 101808Z) or at 2:08pm Eastern Standard Time. The terminal forecast is valid from 18Z on the 10th of the month until 18Z the next day (as shown by 101818). It reports winds from the South or 170 degrees true on the compass rose at 5 knots (17005KT), with a visibility greater than 6 statute miles (P6SM), with an overcast ceiling at 2,500 feet above the airport (OVC025). Temporarily between 18Z and 22Z (TEMPO 1822), the clouds are forecast to be scattered at 2,500 feet and overcast at 7,000 feet. From 0Z, the wind will be from the South-southeast at 8 knots with a visibility greater than 6 miles, overcast clouds at 1,000 feet. From 3Z the wind will be from the Southeast at 8 knots with a visibility of 4 statute miles, mist (BR) and clouds overcast at 800 feet. At 10Z, the wind will be from the East-southeast at 9 knots with a visibility of 3 statute miles, clouds overcast at 400 feet and a probability of 30% (PROB30) between 10Z and 13Z that the visibility will go down to 2 statute miles with light rain (-RA) and mist. Starting at 13Z, the wind will be from 120 degrees true at 5 knots, the visibility will be 2 miles with light rain and mist and the clouds will be overcast at 4,000 feet. At 17Z, the wind will be from 150 degrees true at 15 knots, gusting to 25 knots, the visibility will be half a mile with rain, fog and clouds overcast at 200 feet.

KBOS 101808Z 101818 17005KT P6SM OVC025 TEMPO 1822 SCT025 OVC070 FM0000 16008KT P6SM OVC010 FM0300 15008KT 4SM BR OVC008 FM1000 12009KT 3SM BR OVC004 PROB30 1013 2SM -RA BR FM1300 12015KT 2SM -RA BR OVC004 FM1700 15015G25KT 1/2SM RA FG OVC002

Insert 2.1: Example of TAF

2.4.2 The Low Level Significant Weather Chart

The low-level significant weather prognostic chart provides forecasts for specific future times of weather systems, low ceilings and visibilities, icing and turbulence. An example is shown in Figure 2.3. A legend for the prognostic chart is shown in Figure 2.2.

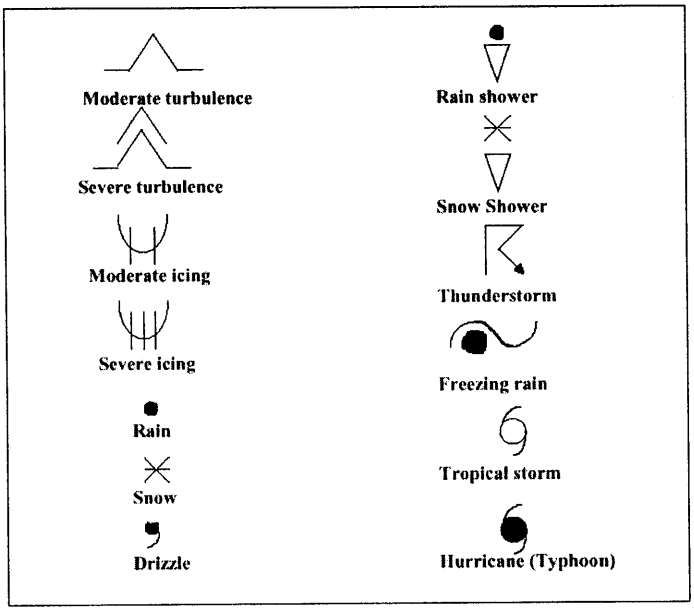

Figure 2.2: Significant weather prognostic symbols

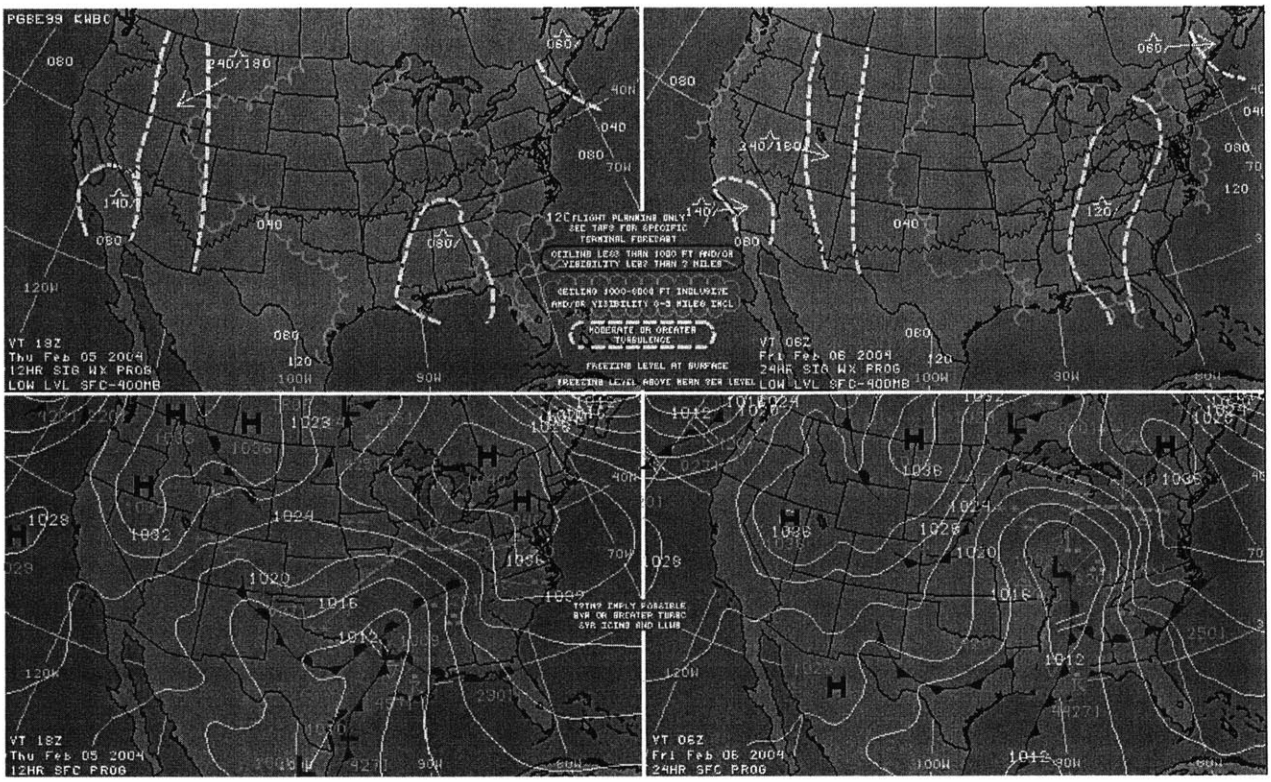

Figure 2.3: Low Level Significant Weather Chart at 10:10am on Feb. 5, 2004

2.4.3 The Radar Summary Chart

The radar summary chart graphically depicts a collection of radar weather reports to depict the location, size, shape, intensity of radar returns, intensity trend and direction of movement, as shown in Figure 2.4. Three levels of intensity are shown on the chart, whereas the first contour represents levels one and two ore weak to moderate returns (light to moderate precipitation); the second shows levels three and four or strong to very strong returns (heavy to very heavy precipitation); the third contour outlines levels five and six representing intense and extreme returns. In addition, the chart shows lines and cells of hazardous thunderstorms as well as echo height of the tops and bases of precipitation areas.

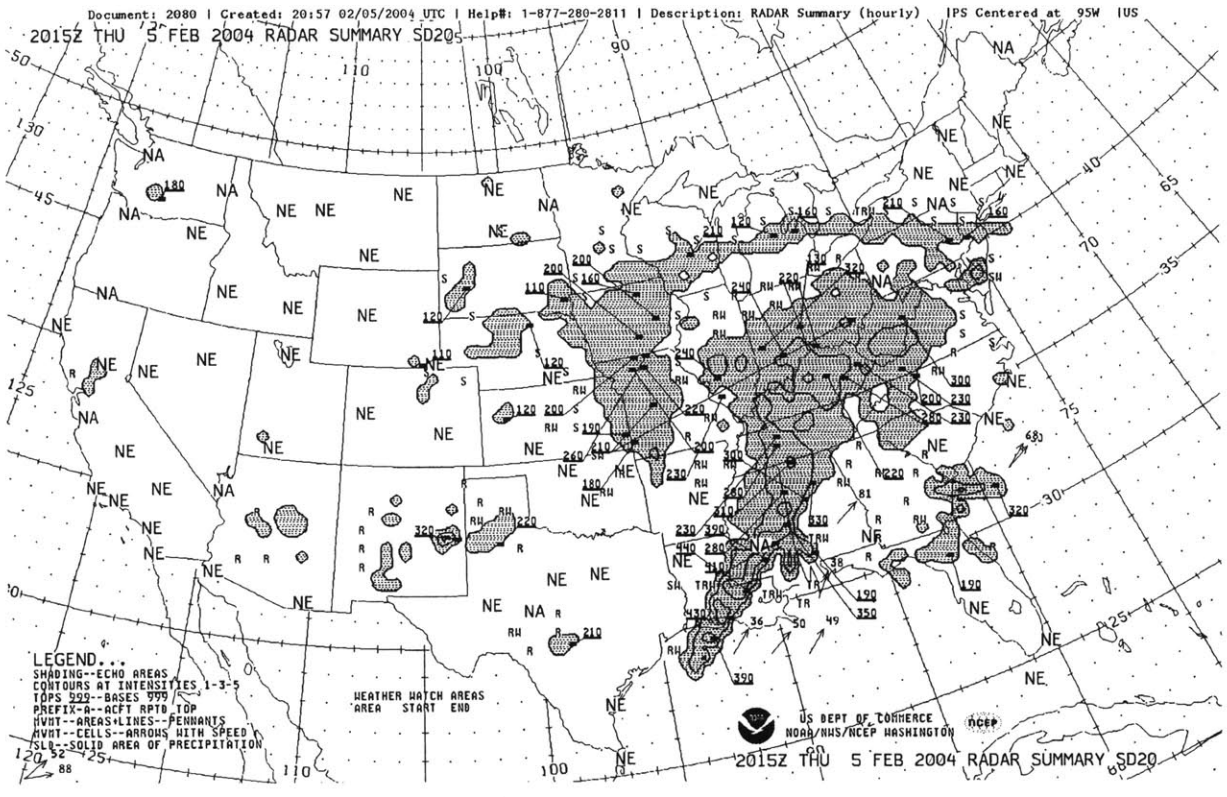

Figure 2.4: Example of Radar Summary Chart

2.4.4 The Flight Path Tool

The Aviation Digital Data Service's Flight Path Tool (*adds.aviationweather.gov*) is a tool available online that provides pilots with means to visualize specific modelled weather conditions such as temperature, humidity level and icing potential. It also shows location-specific pop-up elements of standard weather briefings such as PIREPs and TAFs. One of its most innovative attributes is the ability for users to visualize a vertical cross-section of the weather conditions and PIREPs along a specified route of flight. An example of the flight path tool representation is shown in Figure 2.5.

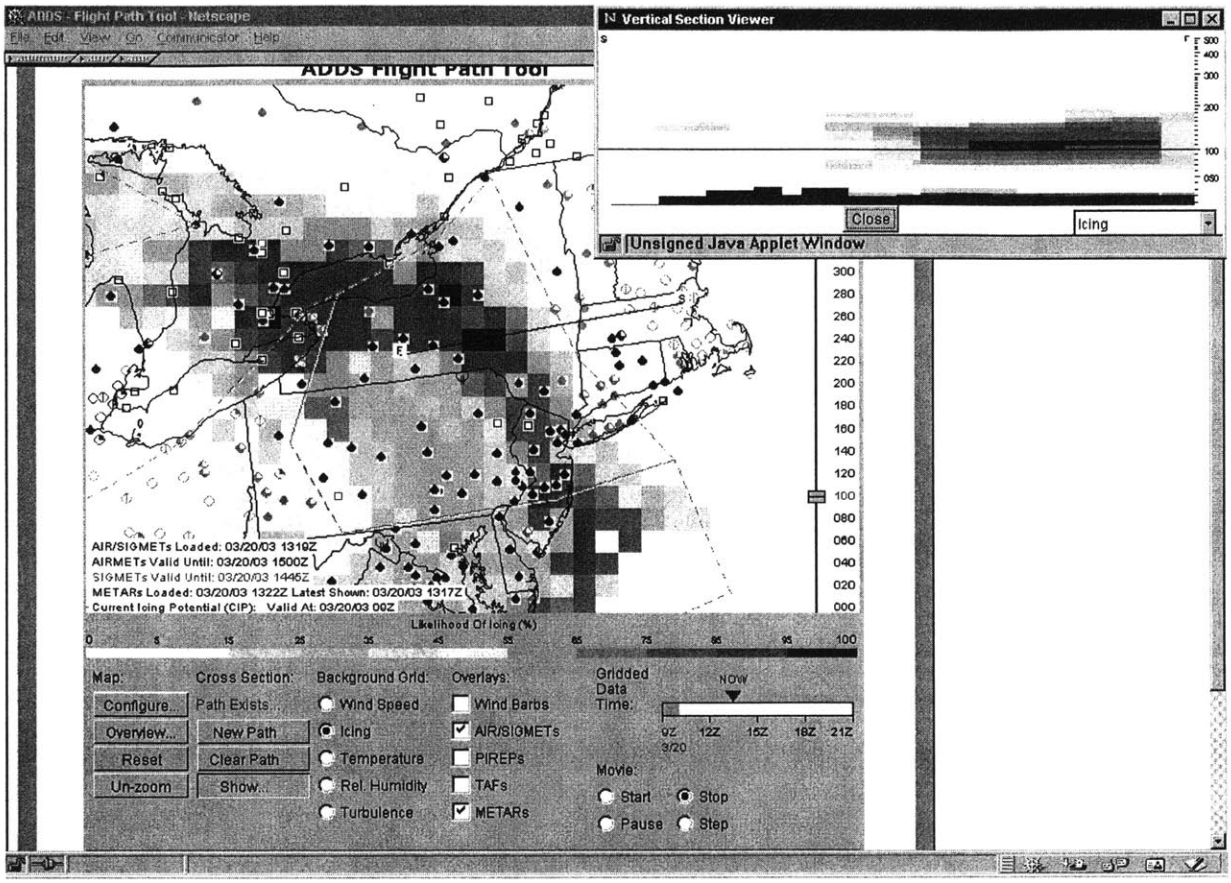

Figure 2.5: Example of Flight Path Tool representation

Shown in Figure 2.5 are two cross-sections of the icing field. The horizontal view shows a cross-section of the icing field at a user-selectable altitude (10,000 feet is the altitude selected in the figure) and the vertical view shows a cross-section of the icing field along a user-selectable route (the route between Norwood, Massachusetts and Cuyahoga County, Ohio is displayed). User-activated AIRMETs and METARs are also shown on the figure. The ceiling information of surface observations (METARs) is indicated graphically for each location where a METAR is available by a circular colored icon. In addition, the full METAR message is shown when the user scrolls over the icon. AIRMETs are shown graphically by dashed lines between AIRMET vertices. Scrolling over the area of the AIRMET, the user is also able to read the full AIRMET textual message. The time for which the information is displayed can be selected by the user by moving the time indicator in the *gridded data time* window. More information on the flight path tool may be found on the website (*adds.aviationweather.gov*)

2.4.5 The AOPA Member Site

The weather pages of the Aircraft Owners and Pilots Association members' website (*www.aopa.org*) provides textual reports and a series of imagery including satellite, radar, surface forecasts with convective weather information generated by the weather information provider Meteorlogix. An example of the surface forecast is provided in Figure 2.6.

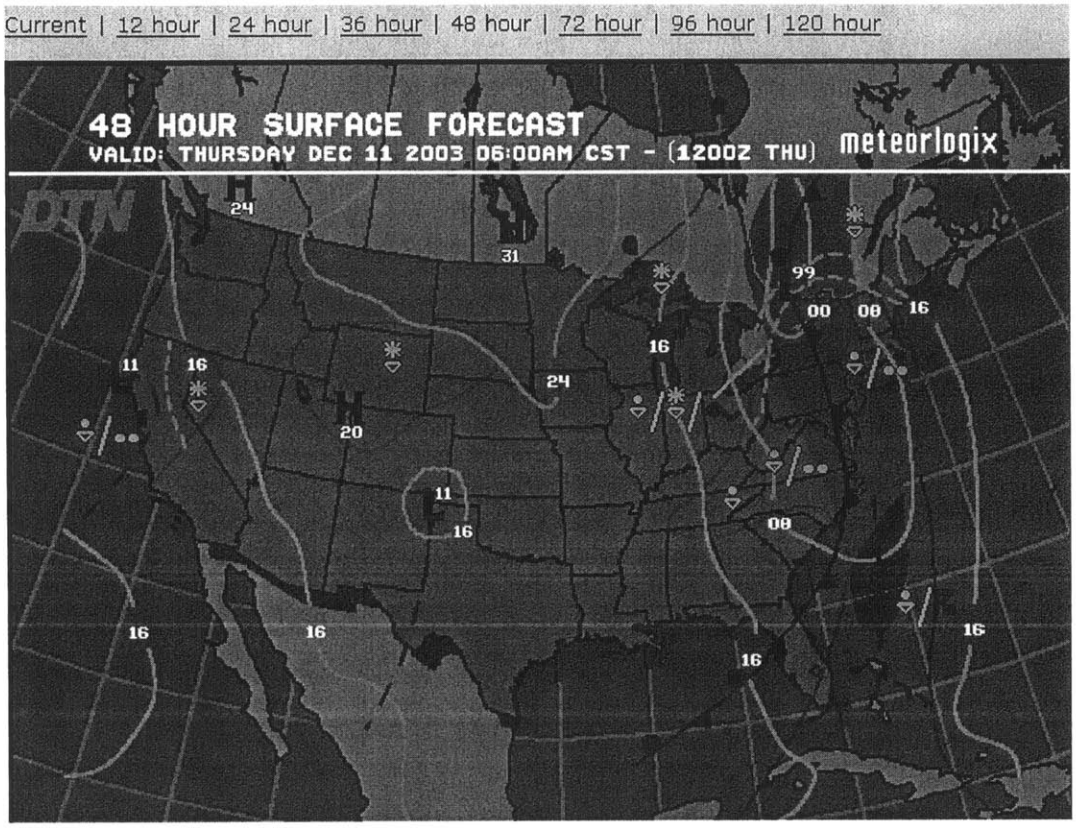

Figure 2.6: Example of a Surface Forecast

The legend for the figure is available on the website. As a brief overview, the figure provides information about:

- cold and warm fronts (e.g., the blue line extending along the US East Coast shows a cold front),
- probability of precipitation (e.g., the solid colored area in the vicinity of the cold front shows an expectation for precipitations greater than 50%) and whether they are convective or non-convective precipitations (e.g., solid areas colored red refers to convective precipitations and green refers to non-convective precipitations),
- location of where the freezing level meets the surface (shown by the light green dashed lines),

- the expected type of precipitation over a geographical area (shown by the yellow triangle, circle and star icons), isobars (shown in grey and labeled according to the pressure level) and
- the location of pressure systems.

2.4.6 The Collaborative Convective Forecast Product

The Collaborative Convective Forecast Product is used by airline dispatchers and traffic managers to make decisions with regard to re-routing airline traffic due to convective weather. It provides probabilistic information over a six-hour period of time about the expected thunderstorm activity over geographical areas, in terms of coverage and probability of occurrence (although recently that feature was changed into confidence). An example is shown in Figure 2.7.

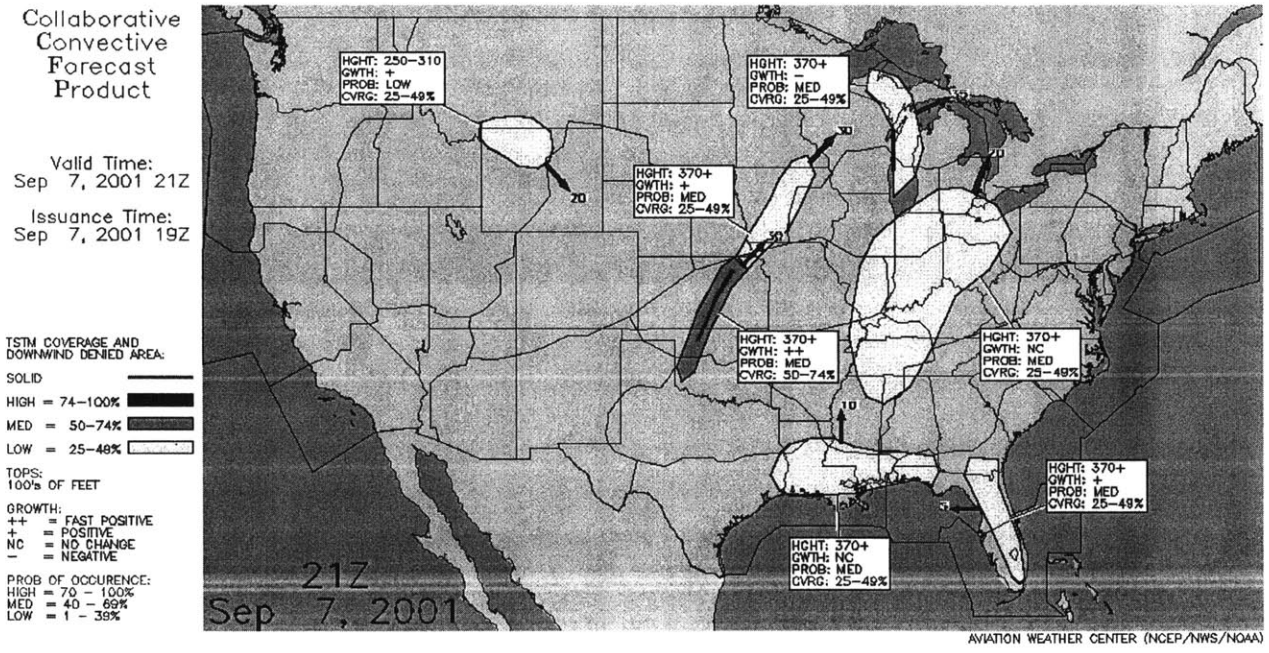

Figure 2.7: Example of Collaborative Convective Forecast Product

2.5 SUMMARY

The first part of this chapter provided an overview of the reasons for concern related to four types of adverse weather phenomena in the problem of adverse aircraft-weather encounters. The second part covered a review of the literature related to the development of weather information system elements including surveillance, forecasting, dissemination and presentation. An overview of the work on weather

information needs was presented. Finally, because weather information tools are discussed and used in the later chapters of the thesis, a brief overview of main tools was also presented. A gap in the literature on a methodology to study ways to improve weather information by considering the human operator as a key element of the system has been identified. Applying a human-centered system analysis, this thesis will address this need.

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3 MODELS OF HUMAN-CONTROLLED ADVERSE AIRCRAFT-WEATHER ENCOUNTERS

In order to identify opportunities to improve weather information, an in-depth systems analysis of the information flow in the adverse aircraft-weather encounter problem was conducted and is presented in this chapter. The analysis consisted of a model-based study of the key elements of the encounter problem and of the interaction between these key elements. The model-based study focused on three main elements of the high-level model shown in Figure 3.1.

The first element, the *situation dynamics*, is shown at the left of the figure. It represents the physical situation involving an aircraft encounter with potentially adverse weather conditions. A more detailed representation of the situation dynamics will be provided in Section 3.2.

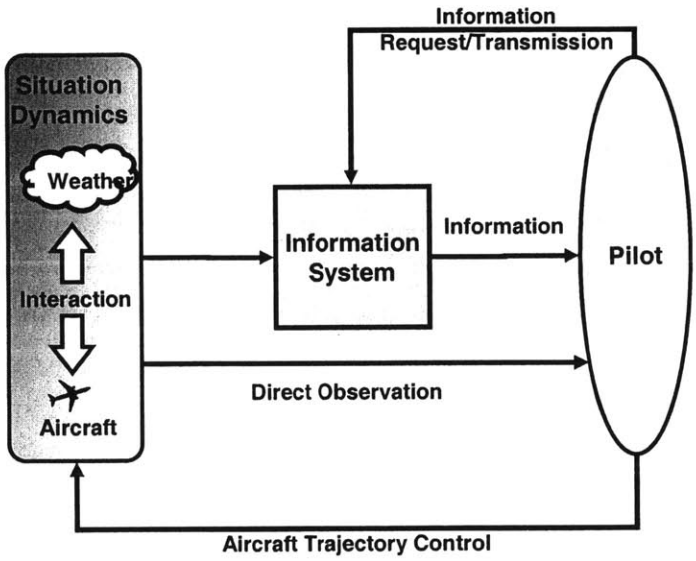


Figure 3.1: High-level model of pilot-aircraft-weather encounter

The second element, the *information system*, is shown at the center of the figure. It represents in an aggregate form the various components of systems that serve to measure and predict the state of the meteorological environment and provide information about it to the pilot. A more detailed model of the information system architecture will be provided in Section 3.3.

The third element, the *pilot*, is shown at the right of the figure. It represents the perceptual, cognitive and physical processes that allow the human pilot operator to process information and interact with his or her

environment in the context of weather-related flying tasks. A more detailed representation of the model of pilot sub-model will be provided in Section 3.5.

The information flow between the three sub-models during a flight is represented in the figure by arrows. As shown in the figure, the information system transforms physical data detected in the physical situation dynamics into information available to the pilot. Alternatively, the pilot may acquire knowledge of the situation dynamics via *direct observation* (visually, aurally or proprioceptually). The Pilot may in turn interact with the information system to request new, updated or different information, as depicted by the information request arrow at the top of the figure. Finally, the means by which a pilot is able to influence the situation dynamics is through his or her interaction with the aircraft via aircraft systems management and control.

The high-level model introduced in Figure 3.1 constitutes a basis from which detailed models can be developed for each of the three elements identified. Prior to presenting the models, Section 3.1 will explain the process that was used to develop and validate the models with Subject Matter Experts (SMEs). The models will be presented in Sections 3.2 through 3.4, respectively. In Sections 3.5 and 3.6, two frameworks are presented that articulate specific aspect of the adverse aircraft-weather encounter problem. The first one, the framework of temporal decision-making, explains the role of pilots' time-varying weather mental model and tasks in the context of weather-related planning. The second framework articulates means to assess the performance of weather forecast in a way that matches pilots' trajectory-centric perspective. Finally, Section 3.6 summarizes the key observations.

3.1 MODEL DEVELOPMENT AND VALIDATION

The descriptive models and framework presented in this chapter were developed using inductive and deductive reasoning and covered the steps listed below:

1. Literature review
2. Review of research programs
3. Review of current technical developments
4. Field observations
5. Surveys and experiments with pilots
6. Analytical model development
7. Multiple audit sessions with experts
8. External review through focused interviews with 10 national experts

A review of current weather-related research programs in the United States and internationally was also conducted via participation in congresses, conferences and meetings. Finally, a review of the latest technical developments in weather information products available was also conducted through market research and consulting. Some of these results are also presented in Chapter Two.

The author conducted over 1,000 hours of field observations of weather-related decision-making while acting as an *observing member of the crew* in the cockpit of ten international and domestic air carriers and during personal flying duties as a commercial pilot with a non-scheduled airline and as a general aviation pilot. These observations served as a basis for articulating questions in a web-based survey on pilot information needs for operating in icing conditions which is included in Appendix C, and for conducting an experiment on the influence of icing information on pilot routing decisions which is included in Appendix D.

Based on a system analysis, the models and framework were developed to represent important elements in the adverse aircraft weather encounter. The high-level model served as the structure of an analytical decomposition of the problem into three main models. Each of the models was developed to capture the most important elements of the problem. The model of situation dynamics provided an abstraction of the most important of the physical problem. The model of information system architecture provided a decomposition of the most important weather information system elements. The model of pilot articulated the most important constructs of information processing in the context of weather-related decision-making. Two frameworks to further explain the relationship between the key elements of the problem were developed. The framework of temporal decision-making built on the understanding of the role of time in weather-related planning and decision-making in the context of dynamics situations and time-varying information. The second framework, the framework of integrated space-time weather forecast assessment, was developed to provide means to influence the design of a key element of the weather information system, forecasts, in a manner that is consistent with pilots' perception of the situation dynamics. The development process was complemented with multiple audit sessions with two aviation weather subject matter experts, including a cockpit human factors expert and a consultant in cockpit information systems and captain for a major US air carrier.

Following the initial model development, an external review of the models was conducted via interviews with ten independent aviation weather subject matter experts (SMEs). Each external reviewer was carefully selected for his or her expertise in either aviation meteorology, aviation weather operations or both. Eight of the SMEs selected were pilots, with experience ranging from general aviation to airline

flying and including military flying as well as production and meteorological flight test. Nine of the SMEs were also nationally or internationally recognized aviation meteorology experts. Their expertise had either been acquired through meteorological education or through extensive work in the field of aviation meteorology as part of national and international aviation weather programs. Three of the meteorological and aviation experts are also accomplished authors of books and articles widely published on the topic of aviation meteorology. Table 3.1 reviews the respective flight- and weather-related credentials of the ten SME reviewers based on the types of organizations they work for.

Table 3.1: Summary of flight- and weather-related credentials of the subject matter expert reviewers

SME Reviewer	Flying Experience	Flying Affiliation	Meteorologist	Meteorological Affiliation
1	Commercial & GA	-	Manager	National Meteorological Research Institution
2	-	-	National Weather Team Leader & Researcher	National Meteorology Research Institution
3	-	-	Convective Weather Expert & Researcher	National Meteorology Research Institution
4	Environmental & Production Flight Test	Civil Aviation Authority	Meteorologist & Author	Major University
5	Production Flight Test	National Aeronautical Research Institution & Major Aircraft Manufacturer	Icing Researcher	National Aeronautical Research Institution
6	Environmental Flight Test & Military	Military & National Meteorology Research Institution	Meteorology Consultant & Researcher	National Meteorology Research Institution and Consulting
7	Major Air Carrier	Major Air Carrier	-	-
8	Commercial & Military	Military	Weather Team Leader	National Meteorology Research Institution
9	Major Air Carrier	Major Air Carrier	Author of Widely Read Aviation Weather Book	-
10	Flight Instruction	National Pilot Organization	Widely Read Author of Aviation Weather Articles	National Pilot Organization

Three of the ten SMEs were interviewed in person and the others were interviewed by phone. All interviews were conducted with the support of colored graphical material (as shown in Appendix F), either on paper (for all three in-person interviews and two of the phone interviews) or in electronic format.

For each model and framework, the SME reviewers were asked to rate their level of agreement on a three-point scale as either: 1) I agree with the model; 2) I disagree with the model; 3) I generally agree with the model but have comments for modification or improvement. The comments were collected and documented by the author during each interview. It was found that no SME reviewer disagreed with any of the models or representations. Most comments related to some details of the models and served to

progressively refine the models. The models are shown in the following figures: Figures 3.1 through 3.8, Figures 3.10 through 3.13, Figure 3.17 and Figure 3.18. Appendix F contains the details of the focused interview study, including a description of the models presented, the protocol and the results.

3.2 MODEL OF ADVERSE AIRCRAFT-WEATHER ENCOUNTER SITUATION DYNAMICS

The notional model that serves to represent the physical aircraft-weather encounter Situation Dynamics is shown in Figure 3.2. In this notional model, the potentially adverse weather is represented by an aviation impact field, which is a region of space characterized by one or more meteorological attributes that impact aviation operations. The aircraft state is represented by a four-dimensional aircraft trajectory which traverses the aviation impact field and the aircraft exposure to the weather field is represented by the interaction between the aircraft trajectory and the aviation impact field.

As shown in Figure 3.2, the aviation impact field is spatially distributed and temporally varying and may be represented with one or more continuously distributed variables. The contour lines shown in the figure represent an example of a spatially varying value of field attribute. The aircraft trajectory can be represented in four dimensions including three dimensions of space and one of time. The representation captures the time-varying aspect of the problem and can serve to analyse situations over intervals of time in the past, the future or both.

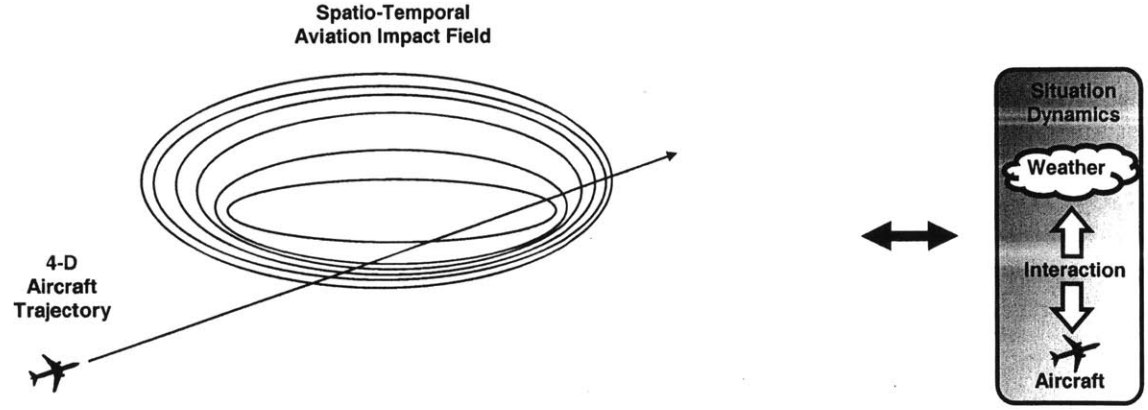


Figure 3.2: Notional model of aircraft-weather encounter situation dynamics

The aviation impact field can be constituted of four types of aviation impact attributes, including:

1) Values describing the physical state of the atmosphere: The aviation impact field may be constituted of physical properties which are described by their values. For example, the temperature, pressure and density fields constitute aviation impact fields.

2) Measured values: The aviation impact field may also be constituted of measured values, based on either in-situ or remote sensing measurement techniques. Examples include radar reflectivity fields, cloud fields and liquid water content (LWC) fields.

3) Modelled values: The aviation impact field may be constituted of modelled values of either physical properties, measured values or other variables. These values may be modelled in the future, in which case they are outputs from weather forecasts, or in near real-time, in which case they are outputs from weather nowcasts. Examples of nowcasts include surface analyses depicting pressure systems (e.g., highs and lows), fronts, dry lines, convergence lines, sea breeze fronts and outflow boundaries. Examples of forecasts of physical properties include temperature forecasts; examples of forecasts of measured values include radar reflectivity forecasts.

4) Instantaneous risk to flight operations: Finally, the aviation impact field may be constituted of attributes that represent the instantaneous risk to a class of aircraft of being exposed to a given weather phenomenon. In this context, instantaneous risk refers to the risk of unit exposure to the field. According to a generalized risk model based on reliability theory, the probability of a loss event along a specified four-dimensional trajectory can then be calculated as a function of the instantaneous weather risk field.

The notional model presented in Figure 3.2 is a simplification of the physical situation. A more sophisticated representation of the weather field may include the identification of regions of high risk that may be desirable for aircraft to avoid, and the depiction of areas where traffic flow is constrained or restricted and that are therefore not usually available for adverse weather avoidance trajectories. Moreover, elements of aircraft trajectories that are of particular significance for aircraft operations may also be represented. This more exhaustive model of the adverse aircraft-weather encounter Situation Dynamics is shown in Figure 3.3.

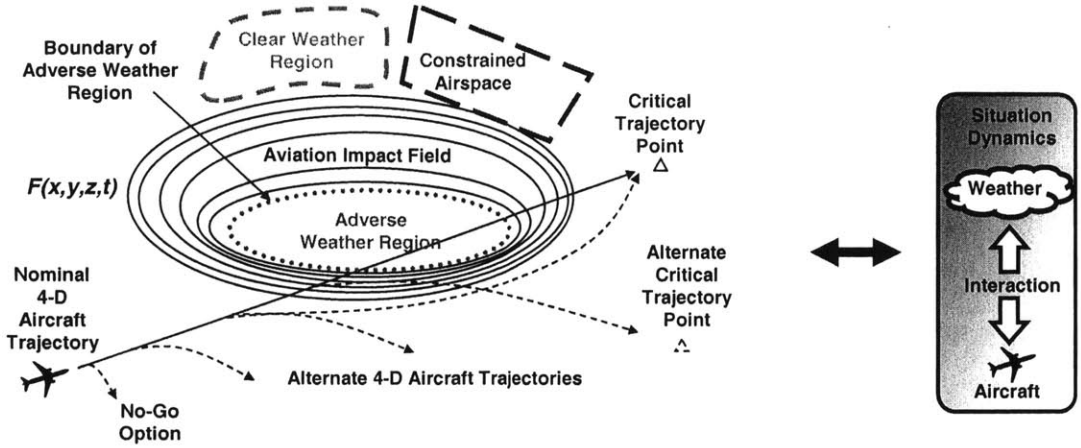


Figure 3.3: Detailed model of aircraft-weather encounter situation dynamics

As depicted in Figure 3.3, a subset of the aviation impact field may constitute *adverse weather regions* which are characterized by some criteria related to the field attributes and that an aircraft trajectory should avoid. In cases in which the adverse character of the weather conditions can be determined specifically, then the appropriate *boundaries of adverse weather regions* may be identified. In addition, a subset of the aviation impact field may be identifiable with a high level of confidence as a region clear of adverse conditions; this is labeled a *clear weather region.*

Finally, a *constrained airspace* is depicted in the model represented in Figure 3.3. It constitutes a subset of the navigable atmospheric airspace that may place restrictions on aircraft operations. Examples would include Special Use Airspace (SUA) and airspace restricted by ATC. Other constrained airspace includes altitudes that should not be flown through because of proximity to terrain, lack of radio coverage at low altitude and aircraft performance or operational ceiling (e.g., due to oxygen equipage requirements).

Several four-dimensional aircraft trajectories are depicted in Figure 3.3. These include nominal as well as alternate four-dimensional aircraft trajectories. The nominal four-dimensional (4-D) aircraft trajectory refers to the currently planned aircraft path. The nominal 4-D aircraft trajectory may be articulated in several ways, including: 1) A preliminary flight time window and block of airspace over which a route is planned; 2) Route filed on a flight plan; 3) Route entered in an aircraft flight management system; 4) Segment of route specified in a Standard Terminal Arrival Procedure (STAR). In contrast, an alternate 4-D aircraft trajectory refers to a trajectory that is considered as a possible substitute to the nominal trajectory. Examples are numerous and include: 1) Alternate route due to weather; 2) STAR leading to a filed alternate airport or an alternate STAR; 3) Alternate Standard Instrument Department Procedure

(SID); 4) Alternate possible cruising altitudes or flight levels; 5) Mountainous terrain diversion routings in the case of depressurization or engine-out scenarios; 6) Missed approach procedure.

In addition to defining aircraft trajectories, the model of Figure 3.3 also includes critical trajectory points. These critical trajectory points are locations that have significant importance for aircraft trajectories and are defined as locations in space that constitute extremities of aircraft trajectories and to or from which alternate aircraft trajectory may go. Examples include origin, destination and alternate airports.

The interaction of the aviation impact field with the aircraft trajectory is modeled as the influence of the aviation impact field on the state of the aircraft for the cases of a physical attribute field and a risk field. In the physical attribute field case, the properties of the atmosphere influence the aircraft state. Examples include the influence of the temperature field in changing the temperature of the aircraft, and the influence of icing conditions in changing the aircraft's airfoil through an ice accretion process. In the risk field case, the risk associated with the trajectory is modified as a function of the interaction of the aircraft with the field.

3.3 MODEL OF INFORMATION SYSTEM ARCHITECTURE

The key elements of the aviation weather information system architecture are shown in Figure 3.4. The model includes two principal information loops that both relate to the adverse aircraft-weather encounter situation dynamics. The first information loop, represented at the top of the figure focuses on weather. The second, depicted at the bottom, focuses on the aircraft. In each information loop, five fundamental steps of information processing are identified and include, as shown from left to right: 1) surveillance, 2) modelling or forecasting, 3) other users who play a key role in weather information dissemination, 4) dissemination through the communication infrastructure and 5) presentation or display. The model represents the information available to pilots both outside of the cockpit environment prior to and during flight.

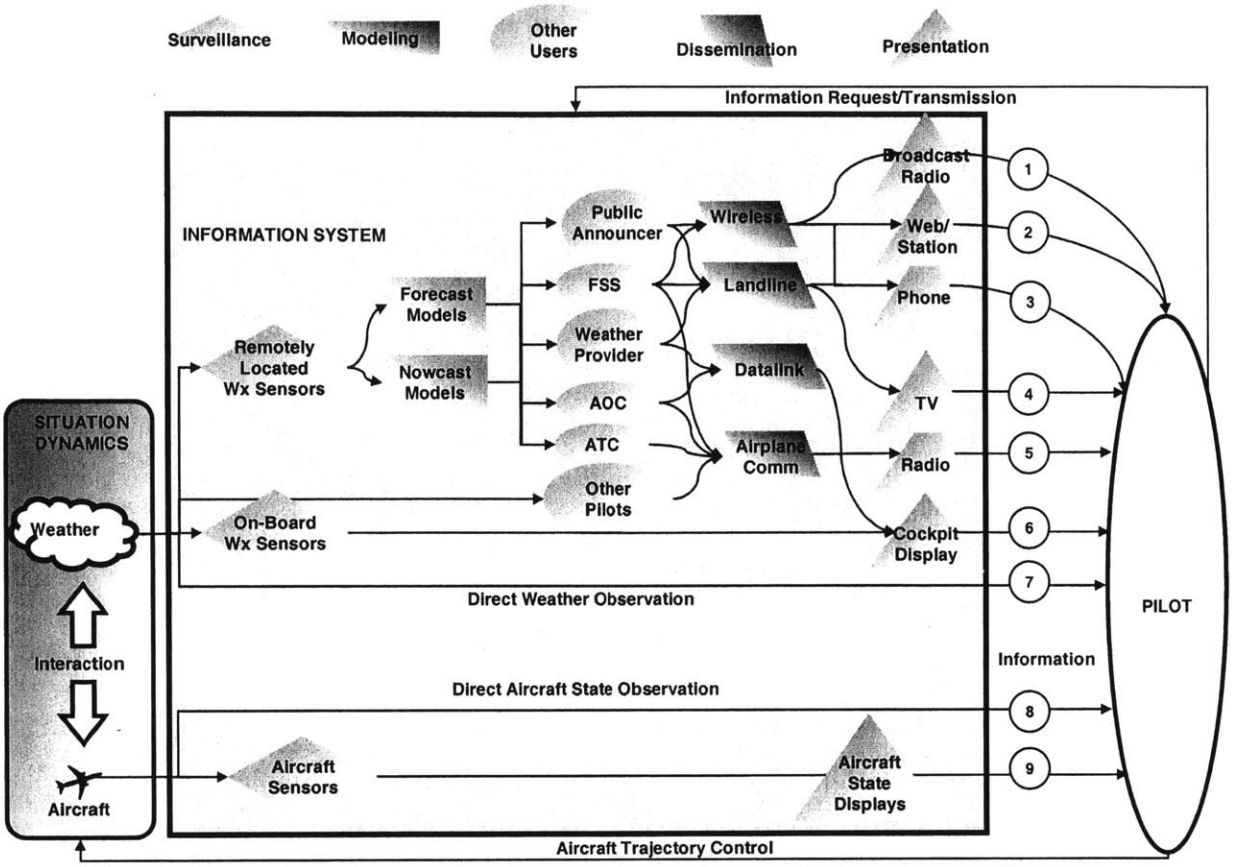


Figure 3.4: Model of current information system architecture

Nine distinct information presentation paths are depicted at the right of Figure 3.4 to provide information to the pilot about the aircraft-weather encounter situation dynamics. The first seven presentation paths (1 through 7) provide weather-related information and the last two (8 and 9) provide aircraft-related information to the pilot.

Moreover, it can be seen in the figure that weather data is detected via four main sensor paths issued from the weather element of the situation dynamics: 1) remotely located weather sensors (leading to presentation paths 1 through 6); 2) other pilots' experiences with the weather based on their observations and measurements (presentation path 5); 3) on-board weather sensors (presentation path 6); 4) direct weather observation (presentation path 7).

Remotely located weather sensors refer to weather sensors that are not on-board the aircraft. Most of the weather information available to pilots is actually detected through remotely located weather sensors, which are either ground-based, satellite-based or located on radio-sondes and other aircraft. Examples

include but are not restricted to ground-based weather radar, satellite-based visible and infrared sensors, anemometers, ceilometers, thermometers, lidar and radiometers.

As depicted in the upper portion of the figure, the data issued from remotely located weather sensors may be used as input into weather models that are used to generate forecast and nowcast. Nowcasts are weather model outputs about the current rather than the future state of the atmosphere; examples of nowcasts include surface analyses with front depictions, radar mosaic and model outputs of current icing and turbulence conditions such as the Current Icing Potential (CIP). By comparison, weather forecasts include weather model outputs applicable at future time horizons. Two methodologies have been distinguished to generate weather forecasts (Mueller, 2003): 1) observation-based systems (also called data fusion or expert systems) that use current conditions and trends to forecast weather such as convection and 2) numerical models that assimilate radar and satellite data and that are used for example to forecast ceilings and visibilities.

Since the information that is generated from weather models is processed away from the aircraft, it is then disseminated as shown in Figure 3.4 via a variety of communication links and representation displays that are highly dependent on the phase of flight. On-board weather sensors refer to weather sensors that are located on-board the aircraft. A variety of sensors may potentially be located on the aircraft, including airborne weather radar, temperature probes and ice detection systems. The information issued from these sensors is typically presented via cockpit displays, thermometer face and warning systems (presentation path 6). Finally, direct weather observation mainly refers to the pilot's eyes, which can survey the weather conditions directly (presentation path 7).

It can be noted that via sight, touch, hearing and through his or her vestibular system the pilot may also be able to infer the state of the atmosphere by reading the state o the aircraft affected by the weather. This information loop is represented in the model of information architecture under information presentation path 8). Useful information may be gathered by the pilot for example upon flying through turbulence, hail, rain and icing conditions.

Other pilots may also contribute weather information that they may observe either through direct observation or via airborne sensors. This information would typically be available to the pilot through three information paths. The first one consists of reading pilot weather reports (PIREPs) as part of standard weather briefings, either textually or aurally. Another one consists of obtaining that information through air traffic controllers that were in communications with other such aircraft. Finally, a pilot may

overhear that information directly as part of the *party-line* information when other pilots are communicating with ATC. Both ATC communication and party-line information would be disseminated over the radio and hence through presentation path 5 shown in Figure 3.4.

Figure 3.5 and Figure 3.6 illustrate the subsets of elements of Figure 3.4 that are relevant for each phase of flight. In the pre-flight phase, information is available to the pilot via the help of weather personnel such as public announcers, commercial weather providers and the Flight Service Station (FSS), as shown in Figure 3.5. The communication links used includes landline and wireless networks for a variety of appliances available at home, including broadcast radio (presentation path 1), the worldwide web, including the Direct User Access Terminal (DUAT, presentation path 2), telephones (presentation path 3) and television (presentation path 4). In addition, commercial vendors also sometimes provide specific weather computer terminals or stations available at Fixed Based Operators (FBOs) that provide other aircraft services at airports; this is displayed as part of presentation path 2.

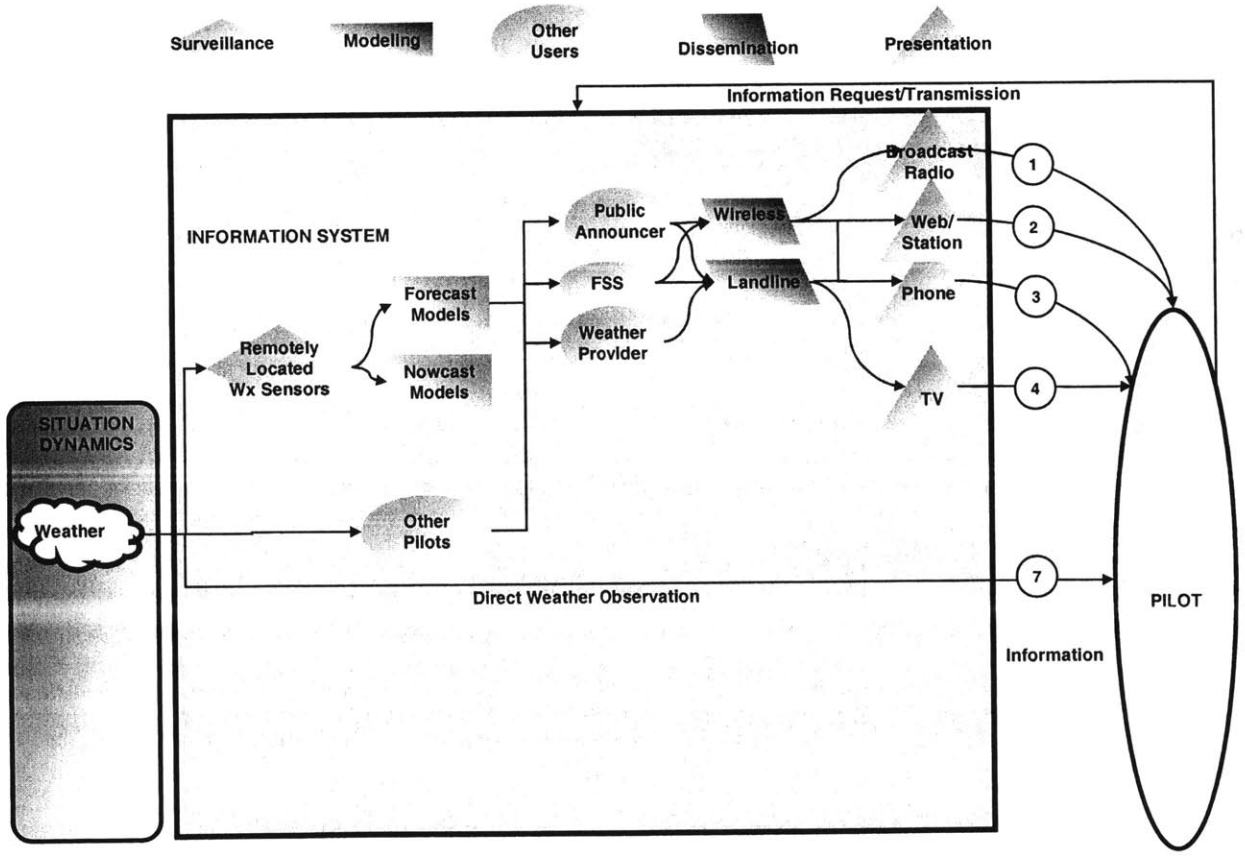


Figure 3.5: Model of current information system architecture (pre-flight)

During the flight, a complementary weather information infrastructure is available to the pilot, as shown in Figure 3.6. Personnel and automation specifically involved with aviation operations may support the weather information system. Weather information may be provided via radio communication (corresponding to presentation path 5) by ATC, by the Airline Operations Center (AOC) in the case of airline operations, by other pilots and by a FSS. In addition, weather information datalinked by the AOC or weather providers may be available via a cockpit display (presentation path 6).

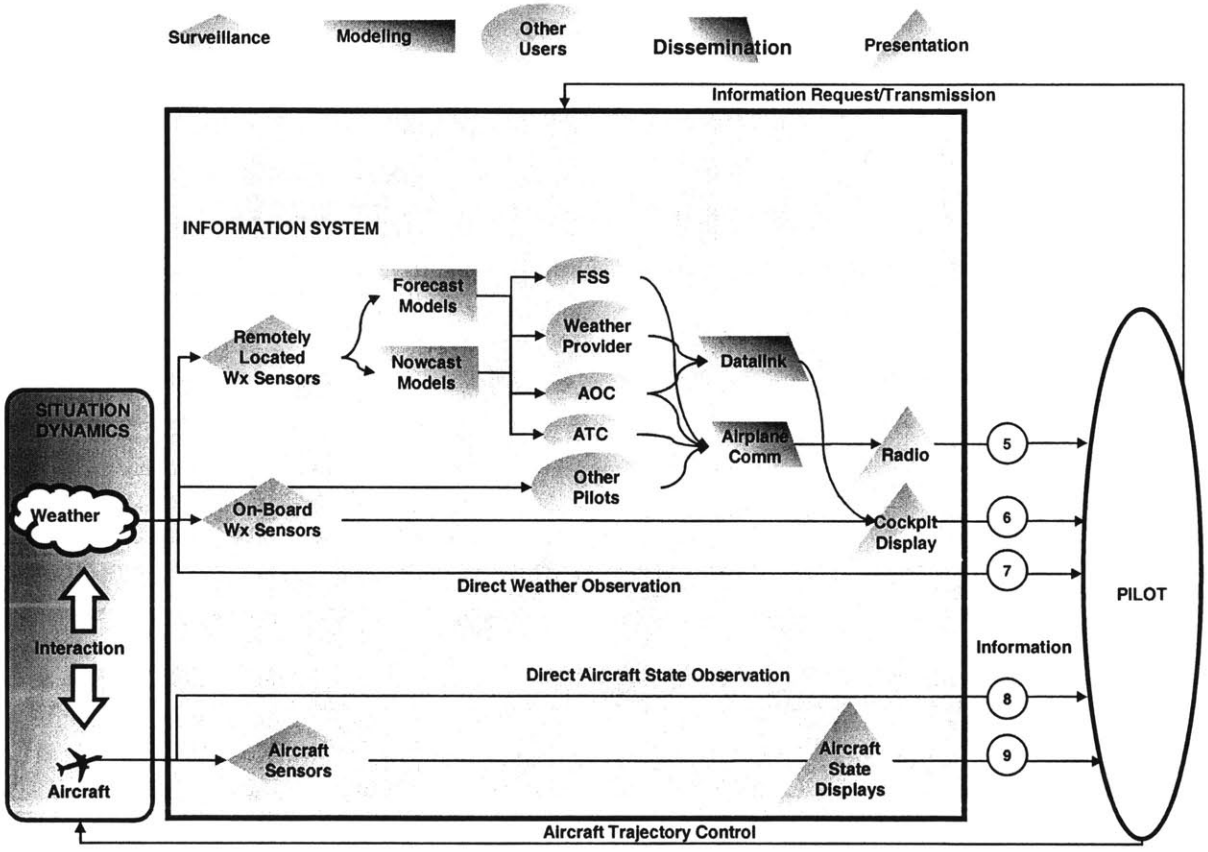


Figure 3.6: Model of current information system architecture (in-flight)

Weather information surveyed through on-board weather sensors is presented to pilots through cockpit displays (presentation path 6). Finally, the information flow corresponding to direct weather observation is depicted as presentation path 7, which is characterized by information about weather conditions that are observable to the pilot.

As shown in Figure 3.4 through Figure 3.6, the model also represents how pilots may interact with the information system via information request and transmission. This interaction may involve the control of airborne weather sensors, the request for update of information disseminated by voice or datalink and/or

an interaction with displays of weather information via page selection and graphical manipulation. A pilot's transmission of weather information may include the dissemination of PIREPs with the FSS, ATC or via automation. Such information may ultimately be included as part of numerical weather models.

3.4 MODEL OF PILOT AND COGNITIVE TASK ANALYSIS

A model of a generic pilot's cognitive processes was developed and is presented in Section 3.4.1. In order to study weather-related decision-making exhaustively, a cognitive analysis of weather-related tasks of an airline pilot was also conducted and is documented in Section 3.4.2. The results from the cognitive task analysis are used as a building block for the framework developed in the next section, Section 3.5.

3.4.1 Model of Pilots' Cognitive Processes

The model of pilots' weather-related cognitive processes was developed based on a review of the literature on cognitive processes. This modeling exercise was informed with insights gained from field experience and prior studies of pilots' weather-related decision-making focused on in-flight icing that are included in Appendices C and D. The model integrates Endsley's situational awareness construct (1995), Pawlak's decision processes (1996) and the articulation of the relationship between key cognitive constructs or models proposed by Reynolds et al. (2002). The model is a representation of the cognitive processes of a single pilot operation. It does not attempt to capture the dynamics of a two- or three-pilot cockpit or the more extended operation with air traffic controllers and airline dispatchers of crew resource management. A sociological model of the interaction and the communication issues between each pilot would be needed in such a model, which is beyond the scope of this work.

As shown in Figure 3.7, the model articulates five constructs of cognitive processing, labeled as *situational awareness*, *decision*, *performance of actions*, *plan* and *weather mental model*. As shown in Figure 3.7, all constructs are influenced by training, experience and procedures in ways that will be explained in more details below. A brief overview of these constructs and their relationship is presented here prior to a more detailed discussion of each construct.

The situational awareness construct provides the initial step in information processing. Pilots' situational awareness is also shown to be mostly influenced by their plan construct: in the high workload and time-constrained cockpit environment, pilots tend to process most effectively the elements of situations they

perceive to best match their objectives and plans. Pilots' situational awareness is influenced by their weather mental model, which represents their cognitive representation of the weather influencing their aircraft trajectories. Building on their situational awareness and weather mental model, pilots process information in order to formulate decisions that will influence their performance of actions as well as their plan. A plan construct is articulated in this model separately from the decision construct in order to emphasize their important and distinct characteristics. The decision construct is focused on assessing and selecting output decisions such as plans and actions, while the plan construct is the distinct entity that would exist in the mind of decision-makers about the articulation of their intentions. As shown, the plan is observed to be generated from the decision part of information processing and to influence pilots' performance of action as well as their situational awareness. Finally, the performance of actions construct is the cognitive construct that focuses on interacting with the physical world, and includes, for example the control of aircraft trajectory through the flight controls, the management of aircraft systems and the request for weather and other information. In order to provide a deeper understanding of the role of pilots' cognitive constructs, a more detailed discussion is presented below in relation to each construct.

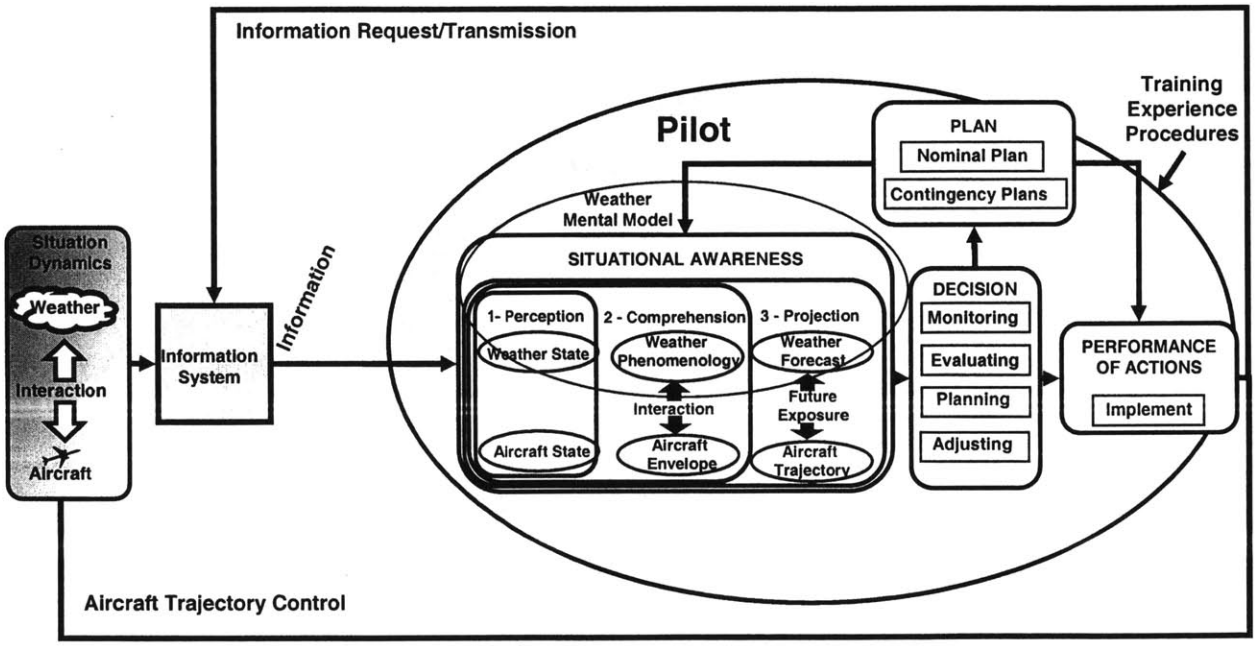


Figure 3.7: Model of pilots' cognitive processes

The situational awareness construct is adapted from Endsley's representation (Endsley, 1995), and emphasizes the role of the processing of the information gathered by the decision-maker who builds a representation of the situation context. As described by Endsley, situational awareness (SA) is articulated here according to three levels. The first level (Level 1) involves the *perception* of the elements of the

situation; the second level (Level 2) involves the *comprehension* of the elements of the situation; the third level (Level 3) involves the *projection* of the states of the situation into the future. In order to help understand the processing of information in the aircraft-weather encounter problem, the SA model includes separate parts related to the aircraft and the weather. At Level 1, the pilot is *perceiving* information elements related to the weather and the aircraft. At Level 2, the elements of the situation dynamics that are *comprehended* by the pilots relate to the weather and its phenomenology, the behavior of the aircraft in its performance envelope, and the interaction between the weather and the aircraft. Finally, at Level 3, pilots may *project* into the future, through a mental model, elements which relate to the weather and its forecast, the aircraft and its future trajectory or trajectories, and the future exposure of the aircraft to the weather field at future times.

A *weather mental model* which underlies the weather situational awareness is also depicted in the model of pilots' cognitive processes and is depicted in Figure 3.7. The pilot's weather mental model is defined as the pilot's cognitive representation of the weather. It includes a representation of the weather conditions as they relate to the weather scenario under consideration. It may include a representation of the weather at specific times in the recent past when and if observations of the weather conditions were available. It also includes a mental representation of the weather four-dimensional dynamics in the scenario encounter in a particular situation, including a cognitive projection of what the weather conditions may be at future times, as well as a representation of how these weather conditions may affect the particular aircraft that the pilot is operating in the situation under consideration.

The relationship between the weather mental model and the situational awareness is such that a subset of the weather mental model serves to build and is part of the pilot's situational awareness construct. It is believed that the sophistication of the pilot's weather mental model is dependent on the level of experience of the pilot, and that this influence permeates through to the pilot's weather-related situational awareness construct. Weather-related education and training can help the pilot better understand the theoretical basis of the observability of the weather, its phenomenology, its four-dimensional dynamics and the influence of weather on flight operations in general, and hence build a more complex and complete general weather mental model. In addition, prior experience in similar situations may help the pilot gain better situational awareness by helping pilots have more sophisticated and potentially accurate weather mental models, as well as by influencing their ability to perceive, understand and project the context of the situations they are dealing with.

Moreover, all three levels of SA are influenced by a pilot's experience. For example, a novice pilot may perceive only a subset of the meteorological elements that would be considered by an experienced decision-maker; the novice pilot may use a projection heuristic that simply follows the evolution mentioned in a weather forecast. An experienced decision-maker, in contrast, may understand much better the phenomenological relationship between weather variables (e.g., cloud coverage, radiation, surface temperature, air temperature and convection) and hence may be able to recognize a scenario in which a forecast is erroneous earlier than a novice upon receiving new evidence about some weather elements. In turn, training and procedures may influence a pilot's level of situational awareness. For example, training or procedures may suggest that a flight planning decision may be made not only on the basis of a nominal plan involving a single flight route, but also that it includes one or multiple alternate or contingency plans such as contingency routings and alternate airports.

The decision construct in the cognitive model is adapted from Pawlak (1996). As shown in Figure 3.7, four elements of decisions are represented in this model and include: *monitoring*, *evaluation*, *planning* and *adjustment*. A somewhat passive process, monitoring involves keeping track of the situation dynamics and seeking to recognize situations that may call for evaluation and/or action. Evaluation refers to examining and assessing the nominal or current courses of action and the factors that may influence the nominal or contingency plans. Planning involves formulating intended courses of action. It may involve the formulation of the nominal plan as well as one or more contingency plans. Emerging from the planning process is a construct that is articulated separately in the model, the plan construct. Finally, adjustment refers to modifying and/or adapting either the plan or the execution according to the results of the previous two elements, evaluation and planning.

The plan construct is a cognitive articulation of the intentions regarding the future of the flight. It includes elements that are stored in the pilot's short term memory regarding the details of the filed flight plan, planned maneuvers and any intentions to request weather information updates. As such, the plan is influenced by procedures and training. Depending on the level of detail of the plan, it may include several additional entities, such as a multiple contingency plans. The nominal plan is defined in this context as the articulation of intended courses of action in the absence of factors which would require contingency actions. A contingency plan is the articulation of alternate intentions that is to be used in case the nominal plan becomes unacceptable for some reason. It is possible that a pilot's nominal plan does not include contingency plans if there is little uncertainty in the environment or if the pilot lacks experience. At the other end of the spectrum, a pilot may generate well-defined contingency plans if the nominal plan is uncertain.

Because it is important that some intent information be shared with other users of the ATC system for proper air traffic management (ATM) under the current paradigm of operations, flights under instrument flight rules require for example that a nominal plan be articulated with a level of detail that includes estimated departure times, routing, requested altitude, estimated time of arrival and estimated airspeed. In addition, under certain forecasted weather conditions at the destination airport, at least one alternate plan needs to be articulated that includes an alternate airport. Procedures, training and experience have a significant influence on pilots' formulation of plans. For example, Federal Aviation Regulations demand that fuel requirements be met for nominal and contingency routes in cases where weather conditions are unfavorable at the destination.

The performance of actions construct includes cognitive activities involved with the implementation of decisions and plans. It is influenced by the pilot's experience and training, and affected by the equipment and input interfaces available to the pilot, such as yoke or stick and rudders to move the aircraft control surfaces and maneuver around, flight management system keys, input devices to the information system, etc.

The model presented above provided a description of *how* information may be processed by pilots. In order to provide a complementary perspective on weather-related decision-making, the following section provides a description of *what* are the key topics of a pilot's decision-making during typical operations.

3.4.2 Weather-Related Cognitive Task Analysis

The key weather-related decisions of pilots in major air carrier (Part 121) flight operations were identified based on a focused interview with an active airline pilot and captain on several types of aircraft (A300, B767 and B757). The interview protocol involved identifying the sequence of flight phases and weather-related cognitive tasks during a typical transcontinental flight. The cognitive tasks were also linked to four temporal functions: pre-flight planning, go/no-go (which also corresponds to the execution of the pre-flight planning function), in-flight planning and in-flight execution. During the interview, the focus was kept on the cognitive tasks that relate to adverse weather phenomena with clearly identifiable adverse weather boundaries, and therefore excluded tasks related to dealing with high density altitude, strong winds and ground de-icing operations.

Table 3.2 shows the results of the focused interviews presented in the chronological order of a typical scheduled air carrier flight. The first column identifies the various phases of flight as they occur. The

second column identifies the weather-related cognitive tasks that occur as a function of the phase of flight. It was found that the pilot would accomplish cognitive tasks using varying planning horizons that depended not only on the phase of flight but also on other factors. In order to capture this, the third and last column identifies whether each cognitive task related to one of the four cognitive functions: pre-flight planning, go/no-go decision-making, in-flight planning and in-flight execution. When more than one function may have been identified for a given cognitive task, then only the function with the greatest planning horizon was listed.

Each phase of flight, cognitive task and cognitive function is explained in detail below according to the order it is presented in Table 3.2. Because the interview focused on Part 121 operations, it can be noted that the results do not include pre-flight weather-related activities that are part of GA and potentially other scheduled and non-scheduled operations and that are very important to these operations.

Table 3.2: Results of focused interview (air carrier operations)

Phase of Flight	Cognitive Task	Cognitive Function
In-Terminal Operations	Weather briefing	Pre-flight planning
In-Terminal Operations	Route planning	Pre-flight planning
Cockpit Operations	Fuel evaluation/selection	Pre-flight planning
Cockpit Operations	Acceptance/rejection of flight plan	Go/No-Go
Cockpit Operations	Cabin crew briefing	Pre-flight planning
Cockpit Operations	Verify/accept clearance	Go/No-Go
Cockpit Operations	Review take-off performance and fuel planning	Pre-flight planning
Take-Off/Initial Climb	Ice protection management	In-Flight Execution
Climb	Manoeuvring around weather	In-Flight Planning
Cruise climb	Determine cruise altitude	In-Flight Planning
Cruise	Updating weather information	In-Flight Planning
Cruise	Horizontal/vertical manoeuvring	In-Flight Planning
Cruise	Re-routing	In-Flight Planning
Top-of-Descent	Descent planning / turbulence avoidance	In-Flight Planning
Descent	Aircraft systems management (anti-ice, turbulence)	In-Flight Execution
Descent	Speed management (turbulence)	In-Flight Execution
Approach Planning	Updating weather information	In-Flight Planning
Approach Planning	Assessing hold vs. weather regions versus fuel	In-Flight Planning
Approach Planning	Dispatch interaction over diversion / Bingo fuel	In-Flight Planning
Final approach	Approach planning w.r.t. thunderstorms	In-Flight Planning
Final approach	Fuel critical declaration	In-Flight Execution

Ten phases of flight were identified by the test subject. *In-terminal operations* refer to a pre-flight phase where the pilot is in the terminal building prior to entering the airplane cockpit. Pre-flight *cockpit operations* refer to activities that are conducted after entering the cockpit while the aircraft is still on the ground. The *take-off/initial climb* phase of flight refers to operations that are conducted in the very first stage of the flight, when the aircraft lifts-off from the runway or as part of the initial portion of the climb phase. The *climb* phase refers to the phase of flight following lifts off, and the *cruise climb* phase refers to the later portion of the climb phase. The *cruise* phase refers to the main portion of long flights. The *top-of-descent* phase refers to the phase of flight during which pilots are planning for the *descent* phase which follows. *Approach planning* refers to that portion of flight which may overlap with the top-of-descent or descent phase that is concerned with planning for the arrival into the destination airport. The *final approach* refers to the portion of flight that is concerned with the implementation of the final approach course and that may involve conducting an instrument approach procedure.

Weather briefing refers to the first cognitive task that the test subject pilot mentioned to accomplish in relation to his flight that requires weather information. Although he may often gather weather information days and hours prior to his flight, he will finalize his weather briefing by reading and analyzing the weather information that is included in the flight plan that he obtains from the airline dispatch office. Route planning was identified separately from weather briefing by the test subject to emphasize the critical and careful assessment of the weather along the route of flight and the potential request for modifications and commitment to the route of flight outlined by the dispatch office.

As part of *cockpit operations*, the test subject identified six distinct cognitive tasks, three of which could also be done in the terminal building instead. The first one is the evaluation and selection of the appropriate amount of fuel to carry for the flight. This cognitive task takes into account the legal requirements that stipulate the minimum amount of fuel to be carried for a flight depending on the weather en-route to the destination. Several weather phenomena may influence these fuel requirements. For instance, if low ceilings and visibilities are expected at the destination, then Federal Aviation Regulations (FAR) require the pilot to file for an alternate airport where the conditions are expected to be better than at the intended destination, and that the aircraft takes off with sufficient fuel to fly to the destination and then to the alternate airport. In addition, depending on the weather conditions, the flight crews also decide how much extra fuel should be carried due to the potential adverse weather along their route of flight or at their destination. In this case, the flight crews may decide to carry additional fuel in order to have flexibility in exercising various options that will be known to them at a later time when they are able to obtain better and/or updated weather information. These options may include alternate routing

that involve longer flight times and more fuel burn than the nominal spatial routing but with a later arrival time at the destination, in which case the extra fuel may allow pilots to enter a holding period. The extra fuel that can be carried on-board the aircraft may be constrained by the maximum gross weight of the aircraft in order to safely take-off or to ensure an adequate climb profile. A poor decision in that part of the flight may lead flight crews to early diversions or requesting special treatment from ATC.

Another key decision involves identifying what the cabin crew briefing items may be, especially as they relate to en-route turbulence or chop. This task is concerned with identifying what the relevant information is to share with the cabin crew about the parts of flight that may be affected by various levels of turbulence or chop according to the weather forecast and the prediction of the location of the aircraft at various stages of the flight. Finally, the most important pre-flight task that was reported involves accepting or rejecting the flight plan. The basis for rejecting the flight plan could involve weather-related reasons such as expected adverse weather on the nominal route and insufficient fuel on-board for the predicted weather conditions.

One of the last two cockpit operations mentioned by the airline pilot test subject is the verification and/or the acceptance of the clearance that is obtained from ATC in relation to adverse weather in the initial portion of flight when the aircraft is almost ready to push-off. Finally, another cognitive task includes reviewing the take-off performance and fuel plan according to the recently obtained clearance in order to execute the take-off and climb phases of flight adequately.

During the *take-off/initial climb* phase of flight, the test subject reported managing the ice protection system according to the potential penetration in visible moisture at temperatures below freezing. Visible moisture refers to clouds and precipitation areas. The test subject also reported that, during the *climb*, he may be manoeuvring around potentially adverse weather regions associated, for example, with convective weather. Finally, in the last stage of the climb, the test subject reported being concerned with selecting a cruising altitude that would be appropriate to avoid flight levels associated with turbulence areas. This cognitive task may involve using the initial flight plan and weather briefing information as well as querying ATC for the recently reported "rides" at relevant flight levels and listening in for *party-line* information overheard from other communications on the same radio frequency.

The test subject reported that during the *cruise* phase of flight, four types of weather-related cognitive tasks were relevant. The first cognitive task involves monitoring the situation during the flight, in order to detect any relevant weather event that may require re-planning. Monitoring is accomplished by various

sub-tasks including direct visual observations for information about adverse weather conditions, scanning with the airborne weather radar, listening and/or inquiring with ATC for potential ride information, and monitoring for the reception of weather information and/or sending an inquiry to dispatch via radio or datalink about weather information. The second cognitive task is more actively geared toward updating weather information, which may be triggered by the monitoring task or other reasons. Weather information may be updated through various means including the ones mentioned in relation to monitoring, but also by contacting dispatch or the FSS. The third cognitive task, horizontal and/or vertical manoeuvring, is accomplished in response to either a need for re-planning that was identified based on the previous two cognitive tasks, or based on other reasons such as ATC request. In both cases, this task requires that attention be paid to the weather conditions along the new vertical or horizontal routes. The fourth cognitive task described, re-routing, is concerned with identifying a plan in order to reach a different airport from the initially planned destination airport. As part of airline operations, this task would normally be done in coordination with the airline dispatch office.

Three specific cognitive tasks were identified by the test subject in relation to the descent phase of flight, and included *approach planning* in order to avoid turbulence areas as much as possible, *aircraft systems management* and *speed management* in order to minimize the impact of potentially adverse weather on the aircraft. The task of approach planning consists of identifying when to initiate a descent in preparation for the approach into the final destination and what descent profile to use. Weather-related *aircraft systems management* may include the management of ice-protection systems, the management of the cabin via the cabin crew, and of the speed control mechanisms such as descent path, thrust and other aircraft control mechanisms.

Three cognitive tasks were also identified in relation to approach planning. The first one involved *updating weather information* mainly through the reception and processing of the Automated Terminal Information System (ATIS) information. In cases where the airplane may be put in a holding pattern, the test subject identified another cognitive task related to assessing the time it could stay in a holding pattern based on the remaining fuel and an assessment of the amount of fuel necessary to complete the remaining flight legs. Finally, in the case where a diversion may be possible, another cognitive task identified was related to interacting with dispatch over possible diversion destinations and the amount of the minimum amount of remaining fuel with which such a decision would need to be made (also called bingo fuel). In the final approach phase, the test subject identified Approach planning with respect to thunderstorms and the declaration of a fuel critical situation, as appropriate.

As shown in the last column of Table 3.2, it was found that most cognitive tasks (17 out of 23) related to planning, either pre-flight or in-flight. This result shows the significance of weather information in supporting planning tasks rather than execution tasks. It was also found that cognitive tasks accomplished earlier in a flight used greater planning horizons than later cognitive tasks. In other words, while progressing through a flight, a pilot would consider progressively shorter time periods relevant to the flight. In order to bring this discussion further, Figure 3.8 illustrates the relative time horizons that are used in order to accomplish the functions listed in Table 3.2.

Based on the cognitive task analysis, Figure 3.8 illustrates pilots' planning functions according to three distinct temporal horizons. As shown at the top of the figure, pilots' planning horizons are shown to increase from left to right, from reactive to tactical to strategic. Therefore, a pilot's function in the sequence of a flight will evolve from right to left and include, sequentially, pre-flight planning, go/no-go, in-flight planning and in-flight execution, respectively.

Pre-flight planning in the figure corresponds to cognitive tasks that were identified in Table 3.2, namely obtaining a weather briefing, route planning, fuel evaluation and/or selection, identifying the cabin crew briefing items, conducting the briefing and reviewing the take-off performance and fuel plan. As mentioned earlier, the interview focused on major air carrier or Part 121 operations, and did not cover the extensive weather-related pre-flight planning tasks that may occur over several days prior to the flight relevant to other operations such as GA and Part 135 operations.

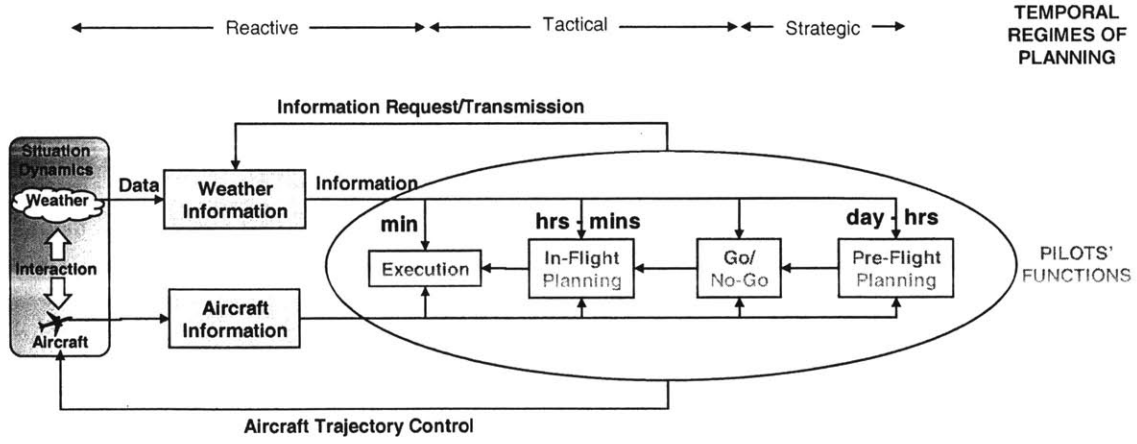


Figure 3.8: Temporal representation of pilots' functions

A correspondence between pilots' functions and their temporal regimes of planning was established, as shown in Figure 3.8. *Strategic* planning refers to the planning horizons considered in pilots' functions such as pre-flight planning. The *go/no-go* decision lies at the transition between the strategic and *tactical*

planning regimes. *In-flight planning* is designated under tactical planning, and the *execution* of plans lies at the transition between tactical and *reactive* planning.

3.5 FRAMEWORK OF TEMPORAL DECISION-MAKING

In order to explain the influence of time in pilots' weather mental models and planning activities, a framework of temporal decision-making was developed and is presented in this section. This framework builds on two main elements. The first element is the pilots' cognitive temporal representation of weather. It is introduced here as building on an analysis of the state of the art in weather predictability combined with the previously introduced pilot's weather cognitive model. The other element of the framework is the pilot's planning representation which builds on the previously introduced description of the pilot's cognitive tasks and planning horizons presented in Sub-Section 3.4.2.

This section is divided into three parts. First, a model of pilots' temporal weather mental model is presented. Then, building on the temporal model, the framework of temporal decision-making is introduced conceptually and examples are provided. Finally, a summary of the section is provided.

3.5.1 Pilots' Temporal Weather Mental Model

A model of pilots' cognitive representation of how weather evolves and is predictable over time is discussed in this sub-section. Basic principles of weather predictability are first presented to provide an empirical basis for the model. On this basis, a model of the predictability of various weather phenomena over time is presented next, followed by a matching model of pilots' temporal weather mental models

On the predictability of weather

The predictability of particular weather phenomena of interest in the aircraft-weather encounter problem are found to be impeded by various factors in general, including uncertainties of initial conditions, model physics and chaotic evolution of the weather (Lorenz, 1969, 1976, 2001). Insert 3.1 explains the basis of Lorenz' assertions.

Insert 3.1: Statement on the limitations of weather forecasting and Lorenz' premises (2001)

Weather may not be accurately predictable, on the basis of three premises:

1. The physical laws describing the state of the atmosphere are not fully deterministic; rather, they are chaotic in that they exhibit erratic behavior in the sense that very small changes in the initial state of the atmosphere rapidly lead to large and apparently unpredictable changes in the later state;
2. The physical laws describing the state of the atmosphere are not fully known;
3. Numerical modeling that can serve to predict weather uses measurements that exhibit inevitable measurement errors and hence can only solve these equations with errors.

With regard to convective weather, the forecast skill beyond two hours has been found to be very low (National Research Council, 2003). For other weather phenomena such as icing and turbulence, forecasts are still under development but the predictability is also limited by the chaotic properties of the weather. Moreover, atmospheric phenomena have been found to exhibit various characteristic times and spatial scales in a manner that is somewhat correlated. Figure 3.9 shows the approximate characteristic scales in space (dimension) and time (or lifetime) for examples of typical circulation adapted from a figure generated by Lester (1993).

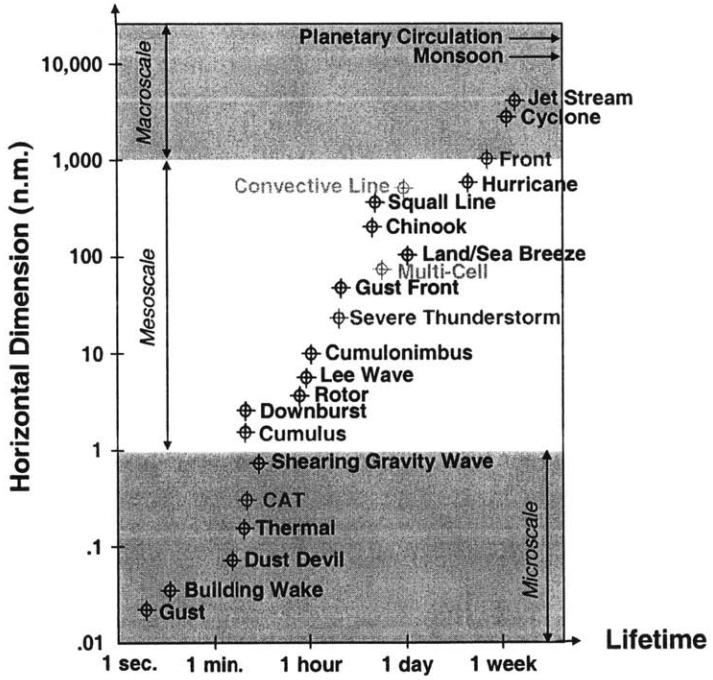


Figure 3.9: Characteristic time and spatial scales of weather phenomena affected by global circulation

Adapted from Lester (1993)

It can be noted that severe thunderstorms are depicted on the figure to fit in the "few hours" characteristic time range. Because the dynamics of weather phenomena affect their predictability over time, the characteristic time scales shown in Figure 3.9 can serve as relative indicators of the predictability of these weather phenomena. For example, the predictability of a convective line of storms may be greater than the predictability of a single isolated thermal. Furthermore, the predictability of observable weather phenomena may be affected by their state of evolution. For example, the predictability of a phenomenon such as a convective cell is much greater following its initiation than during its decay.

Weather Forecast Uncertainty with Forecast Horizon

The extent to which the future states of the weather may be predicted based on the knowledge of current and past states of the system has been found to exhibit some limitations. The state of the art in the ability and uncertainty associated with weather forecasts can be represented using the notional representation of Figure 3.10. As shown, three temporal regimes of weather forecast uncertainty are referenced to the *time of forecast issuance*. They include a *persistence* regime, a *deterministic* regime and a *probabilistic* regime.

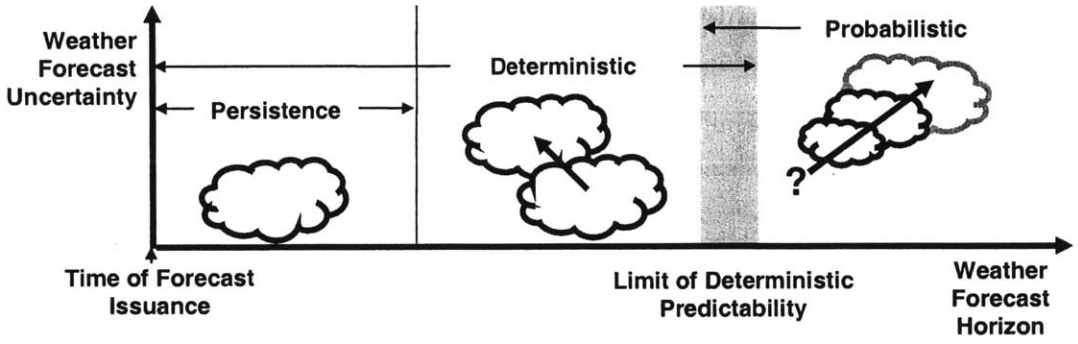


Figure 3.10: Break-down of weather forecast horizons

The persistence regime is associated with a short forecast horizon over which the current conditions are forecasted to persist over the forecast interval per the definition of a persistence forecast (American Meteorological Society, 2000). The deterministic regime is associated with a longer forecast horizon, assumes a deterministic evolution of the weather conditions (American Meteorological Society, 2000) and provides for a given set of initial conditions a predictable evolution of the weather in the future over the deterministic forecast interval.

Finally, the probabilistic regime is associated with a forecast horizon beyond the deterministic regime. The characteristics of the weather phenomena make it impossible to accurately determine the state or

evolution of the weather phenomena. Instead, multiple weather states are possible and the forecast states must be considered probabilistic. The ability to identify the state of the weather conditions in that regime may also be limited by the ability to detect the weather conditions. In that case, the state of the atmosphere may be considered as *apparently stochastic* and only probabilistic nowcasts and forecasts may be appropriate.

The transition between the deterministic and the probabilistic regime may be progressive, as shown in Figure 3.10. It corresponds to a period during which both deterministic and probabilistic forecasts may be appropriate and is referred to a region marking the limit of deterministic predictability. It is dependent on the characteristics and the stage of evolution of the weather phenomena. Moreover, it could be thought of as a regime where the deterministic prediction of some aspects of weather phenomena may be appropriate (e.g., the presence of a front, a storm, a hurricane) but in which the deterministic prediction of other aspects of the weather phenomena (e.g., its location, size, velocity) may not be appropriate.

The temporal representation introduced above is believed to be applicable to describing the predictability of weather forecasts in general. It is also believed to have important implications for the presentation of forecasts to pilots, for training and for decision support of those users with proper weather mental model support. The predictability limits that bound the temporal regimes are dependent on various factors including: the nature of the weather phenomena, the underlying physics, and the characteristic time scales and observability of the weather phenomena.

During the external review with subject matter experts (SME's), the representation described above was found to be valid and raised supportive comments from most of them. The subgroup of SME's with meteorological expertise provided parallels and comparisons with the weather forecasts themselves. SME's with flying expertise discussed the application of the model to specific scenarios that they had experienced and found it appropriate to represent the temporal aspect of their weather mental model, which is the subject of the next section..

Model of Pilots' Cognitive Weather Projection

As explained earlier in the chapter (see Section 3.4 on a Model of Pilots' Cognitive Processes), pilots use weather information, including weather forecasts, to generate their mental projection of the future states of the weather and the aircraft-weather encounter situation. It was decided, for the purpose of this analysis, to adopt the temporal representation of weather forecast uncertainty presented in Figure 3.10 as

the basis for a *prescriptive* reference representation of pilots' temporal weather mental models, as illustrated in Figure 3.11. The term prescriptive here is used in contrast to the term *descriptive* and refers in this context to how pilots *should* rather than *do* use weather cognitive weather projections.

The regimes are referenced here to a *time of information production*, based either on a forecast issuance time or a time of weather observation. When pilots are using multiple sources of information, they may use different reference times for each representation.

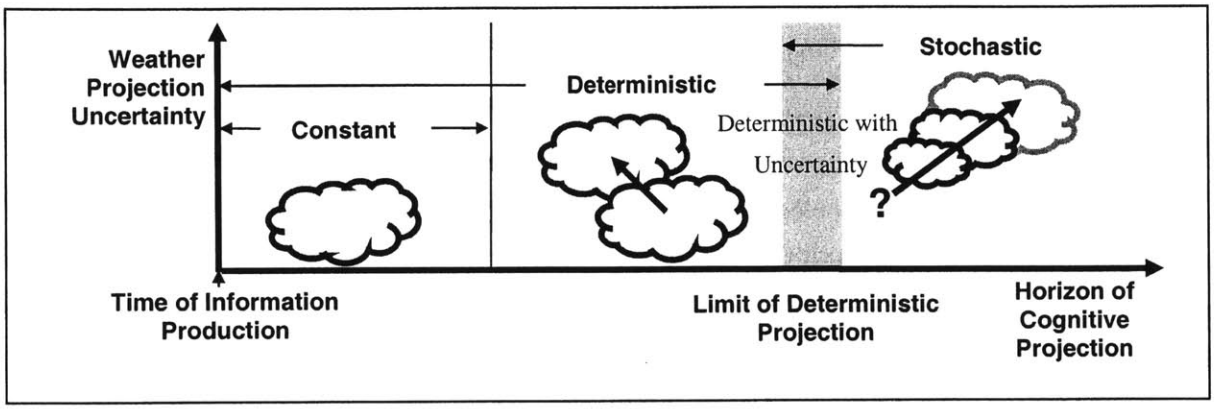


Figure 3.11: Model of a pilot's cognitive weather projection

The *constant* regime of projection applies to the period during which weather is considered static and observations and/or measurements help generate a good representation of the weather conditions over some future interval. It can be observed that, due to the chaotic nature of weather, an accurate weather mental model should not consider a constant representation for a longer time period than the period over which a persistence forecast is appropriate.

The deterministic regime refers to a period during which a deterministic weather mental model provides a good representation of the weather conditions at future states. In order to do that, the weather mental model articulates a representation of the time-varying aspect of the weather conditions. The term *deterministic* is used in this context to mean *whose time evolution can be predicted exactly*. This mental model may be partly based on weather observations and/or deterministic forecasts that provide the pilot with a high confidence about some characteristics of the weather phenomena in the future. Without good observability of the weather conditions and/or without trust in the information, the decision-maker may not be able to generate a deterministic representation of the weather conditions. The constant regime is a subset of the deterministic regime and refers to a time interval over which the representation *can be predicted* as invariant over time.

The stochastic regime, in contrast, refers to a period during which a deterministic mental model does not provide a good representation of the weather conditions, due to the excessive uncertainty and probable error associated with the forecast lead time, the lack of observability of the weather conditions or the lack of information available to the decision-maker. In the stochastic regime, a fundamentally different mental model is required which considers the likely multiple possible weather conditions.

The transition from the deterministic to the stochastic mental model is progressive and the two regimes can overlap, as depicted by the grey time interval in Figure 3.11. Indeed a deterministic mental model may still be appropriate but is reaching the limits of its usefulness and information about the uncertainty of the projection begins to be appropriate. In some cases, the representation may be described as hybrid and involving elements that are deterministic and others that are stochastic and may be referred to as deterministic with uncertainty. For example, the presence of a front, a storm line, a hurricane or the arrival of a bank of fog may be expected with high confidence and a deterministic representation may be used. But the details of when and/or what locations it will specifically impact may not be known exactly and the representation of the future states may be stochastic.

The representation of a decision-making about the presence of adverse weather conditions may also be spatially hybrid, in that an observation at a specific location may support a constant representation (e.g., an icing PIREP or a visibility measurement) but a stochastic representation of the conditions some distance away from the point measurement.

3.5.2 Presentation of the Framework

In order to provide a context for understanding the time varying aspects of weather-related decision-making, a temporal framework combining the two sets of temporal regimes introduced earlier is presented here.

Representation of Cognitive Plan

A pilot's planning horizon is depicted on the abscissa, and the same pilot's horizon for projecting his or her cognitive weather mental model is depicted on the ordinate. A time axis that transits through the various regimes of a pilot's planning and cognitive weather projection is shown in the diagonal of the figure. The origin corresponds in this case to the time of cognition of a decision-maker that is making a plan with freshly produced weather information. The times along the diagonal time axis correspond to a continuous sequence of time events in the future that the pilot is planning for. Depending on the object

and the context of the planning, the time axis has a specific slope in the figure. In this case illustrated in Figure 3.12, the slope is such that the pilot's is able to use a deterministic representation for a portion of the horizon over which he is doing strategic planning. Examples of pilots' tasks evolving in different ways through the matrix are conceptually represented by curves of different slopes in Figure 3.13. A pilot's planning time is considered for scenarios involving weather phenomena of distinct dynamics: routing around a microburst, around a convective front and around an adverse volcanic ash region.

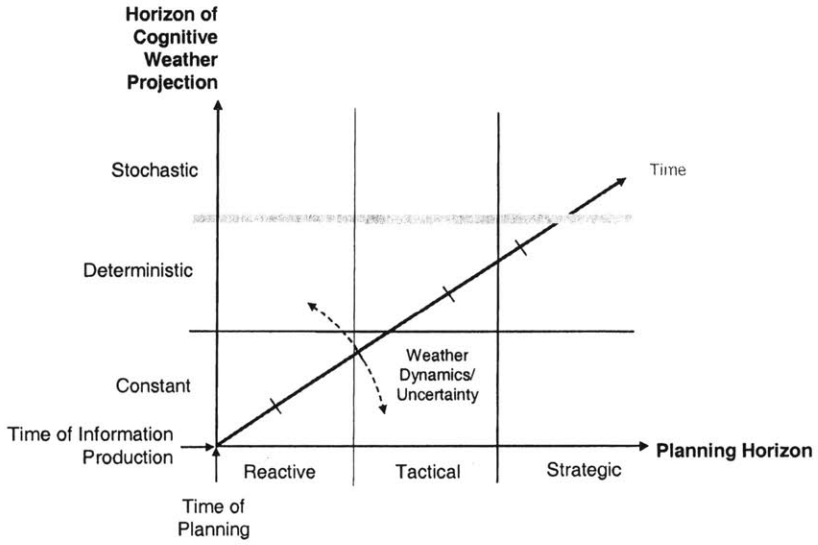


Figure 3.12: Framework of temporal decision-making

As shown in the Figure, the time constants considered for each scenario is fairly distinct, ranging from minutes to days. The various slopes in Figure 3.13 correspond to various levels of dynamics of the weather phenomena.

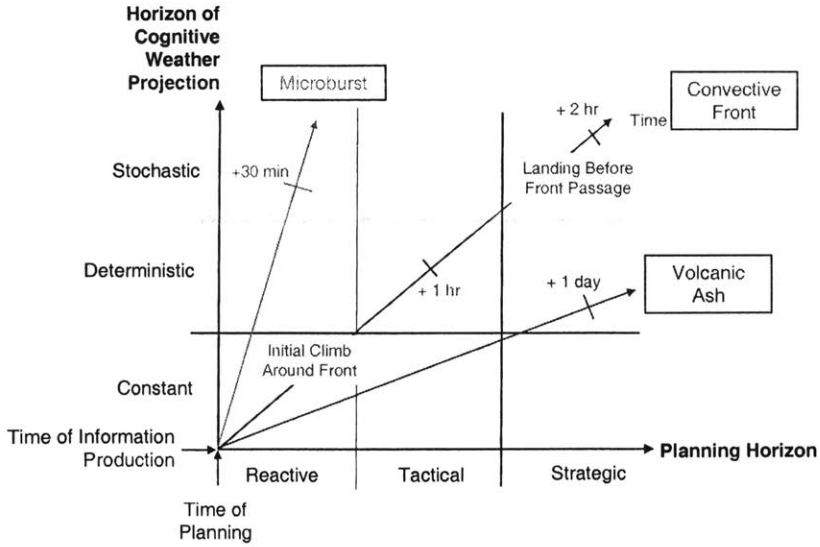


Figure 3.13: Examples of temporal framework applied to planning

Illustration of Framework Use to Examine a Flight Scenario

In the example shown in Figure 3.14, the framework is used to illustrate what uncertainty and planning horizons a pilot may be using in progressing through a typical flight scenario.

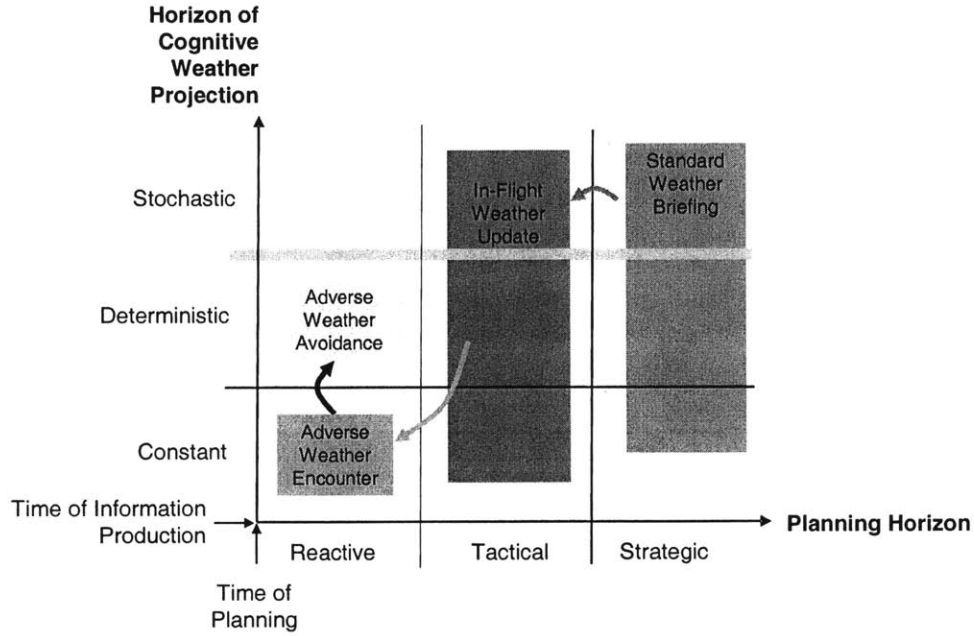


Figure 3.14: Framework applied to through a planned event

Let us consider first that the pilot obtains a standard weather briefing in order to do strategic planning for the flight. The pilot may be using a stochastic representation of the adverse weather conditions that may affect his or her route of flight because the weather conditions are not known with great certainty. It is possible that he or she also has a deterministic representation of some weather conditions such as the presence of a front along the route, etc. His or her full weather mental model may be populated with a representation of a variety of weather phenomena, some for which he or she may use a deterministic or even a constant representation. Upon transitioning into the in-flight portion, the pilot may still have a mix of representations, some of which may be constant for weather conditions that are observable in the immediate vicinity of the flight. A portion of the weather representation of the decision-maker may be deterministic in that he or she has a mental model of the temporal evolution of the conditions, such as the advection of a front or the growth of a storm. Finally, a portion of the weather mental model of the user may be stochastic, in that he or she may not know well whether icing will impact the route of flight because of the lack of observability of the conditions or because there are still 4 hours before the pilot reaches the destination and the storm forecast is stochastic.

Into the flight, the pilot may come near or encounter adverse weather conditions. In this case, she may obtain updated information about the imminent encounter based on direct observation or instrumentation on-board the aircraft. Using this information, the pilot may adjust the existing plan or formulate a whole new plan through reactive planning by considering mostly very near-term outcomes. In order to do that, she may gather information about other locations via the aircraft radio and develop a constant or deterministic representation of the conditions at a location where the conditions are non-hazardous and decide to divert to this location.

3.5.3 Summary

Two new concepts were presented in Section 3.5. First, a model of pilots' cognitive weather projection was introduced to provide a benchmark for discussing how pilots may think about the various levels of uncertainty in their weather representation. The model provides not only a structure for that discussion but also can serve as a prescriptive model describing how pilots *should* think about the forecastability of weather conditions.

In addition, a framework of temporal decision-making was described that articulates two relevant timelines related to pilots cognitive processes, including the one from the model of cognitive weather projection and the timeline relevant to their planning tasks. It was illustrated that the framework can serve to describe pilots' sequence of planned events throughout a flight.

3.6 FRAMEWORK OF INTEGRATED SPACE-TIME FORECAST EVALUATION

There are discrepancies between the quality of forecasts and the value to decision-makers with trajectory-centric perspectives. The terms quality and value are used here in accordance with the definitions provided by Murphy (1993): quality is the correspondence between weather forecasts and observations, while value refers to the usefulness to the users. The framework of integrated space-time forecast evaluation presented in this section proposes a new way to look at the goodness of forecasts in a manner that matches better than the traditional quality assessment methods the perspective of users concerned with aircraft trajectories. The new method is illustrated below to provide means to assess the value of weather information elements such as a forecast's temporal and spatial resolution on the forecast value.

The framework has implications for the generation of weather forecasts as well as the dissemination and presentation of weather information. These implications are discussed in Chapter Five.

It should be noted that the word contingency is used in the context of this section with a different meaning than in the context of the rest of the thesis. In this section as well as in the literature on forecast verification, it is used as a synonym to *possibility*. In the other sections of the thesis, such as in the model of pilots' cognitive processes of this chapter and in the context of Chapters Four and Five, it is used as a synonym to *a future emergency* that must be prepared for.

The first subsection provides a structure for considering pilots' trajectory-centric perspective in evaluating forecasts about adverse weather regions. Building on this result, Sub-section 3.6.2 makes a case for using a space-time reference frame to study the problems of adverse aircraft-weather encounters. The following sub-section (3.6.3) articulates the framework of integrated space-time forecast evaluation and compares it to traditional methods used for evaluating forecasts. A relationship is derived between the value of forecasts and characteristic weather region parameters such as the forecast temporal and spatial resolutions. The relationship enables the quantification of the influence of forecast resolution on the value of forecasts. A summary is presented in Sub-section 3.6.4.

3.6.1 Pilots' Perception of Weather Forecast Accuracy

Table 3.3 provides a contingency table corresponding to the pilots' perspectives in judging weather information. A pilot is found to assess a weather forecast of adverse weather conditions by comparing the prediction to the occurrence of 4-D intersection along his or her aircraft trajectory. For example, if a forecast is provided over a geographical area such as illustrated in Figure 3.16, a pilot may observe that a 4-D intersection was predicted based on the forecast, but no occurrence actually occurred during the flight. According to the pilot's perspective, this case would constitute a False Alarm.

Table 3.3: Contingency table matching the pilot's perspective

		Prediction of 4-D Intersection	
		Yes	**No**
Occurrence of 4-D Intersection	**Yes**	Correct Detection	Missed Detection
	No	False Alarm	Correct Rejection

This contingency table contrasts with the one that is used by forecasters to assess the quality of weather forecasts. Figure 3.15 shows how contingencies used in performance scores are typically calculated for the purpose of weather forecast assessment using a volumetric or area basis. As can be seen in Figure 3.15, forecasted and actual adverse weather regions are compared over the interval of applicability of the weather forecast, which may be much greater than what is needed for pilot use. The contingencies such as correct detections, missed detections, false alarms and correct rejections are computed and serve to generate scoring metrics such as the critical success index, the false alarm ratio and the mean square error. Although these ratios are relevant for assessing the quality of weather forecasts, they are not relevant to assessing how well the forecast performs for a given trajectory such as the trajectory represented in Figure 3.16.

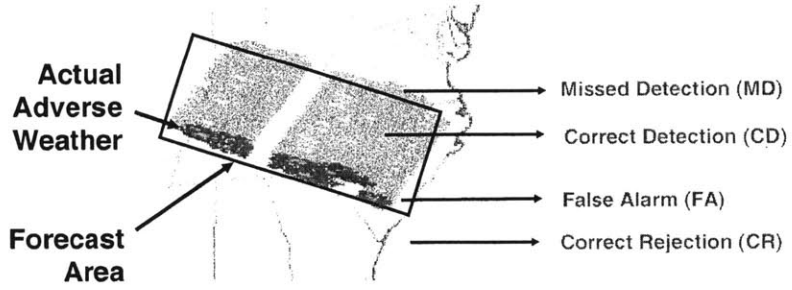


Figure 3.15: Traditional area-based method for identifying contingencies

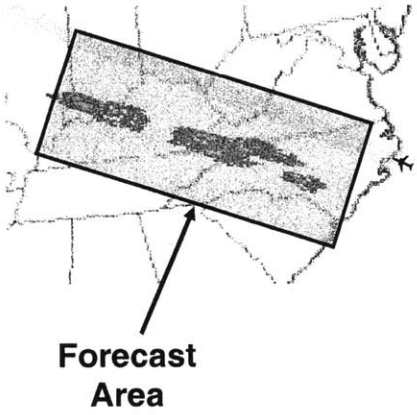


Figure 3.16: Example of a trajectory intersecting a forecast area but that stays clear of the front

3.6.2 Reference Frames for Adverse Aircraft-Weather Encounter Studies

The adverse aircraft-weather encounter problem is a complex problem that can be simplified to a four-dimensional encounter problem under certain assumptions relating to the modelling of the adverse weather field boundaries, its predictability and the relevance of intersections as a characterization of encounters. These assumptions are mentioned below. However, it should be noted that the idea behind the space-time framework can hold outside of the realm of the assumptions mentioned here

For certain weather phenomena, it can be assumed that adverse weather regions and their boundaries are identifiable in space and their evolution is tractable over time. These adverse weather regions described in

space and time are defined here as adverse weather hypervolumes. This assumption is more realistic for adverse weather phenomena for which good measurable surrogate parameters exist to define the limits of the adverse weather regions (e.g., radar reflectivity or cloud cover). However, the general abstraction may be valid to represent the pilot's weather mental model. With regard to the forecasting of adverse weather regions, another necessary assumption is that adverse aircraft-weather encounter problems would occur in the deterministic regime such that a deterministic representation of the adverse weather regions exists.

Figure 3.17 and Figure 3.18 provide illustrations of the simplified four-dimensional adverse aircraft-weather encounter problem in two distinct frames of reference. The spatial position of both the aircraft and the adverse weather region are depicted over a time interval. Using a spatial reference frame, Figure 3.17 shows an apparent 4-D intersection between the hypervolumes occupied by the adverse weather region and the aircraft hypertube. With the temporal resolution selected for the example shown in Figure 3.17, there is an apparent intersection between the aircraft hypertube and the weather hypervolume. In contrast, using a space-time reference frame to study the same problem, it becomes readily apparent that no intersection occurs in the problem illustrated in Figure 3.18. It is interesting to not that Figure 3.17 and Figure 3.18 depict the exact same problem in the two reference frames and different conclusions can be made with regard to an actual intersection prediction.

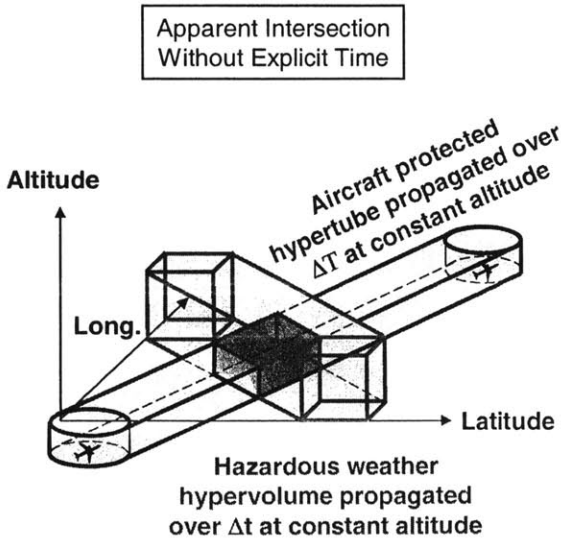


Figure 3.17: Spatial representation of four-dimensional intersection

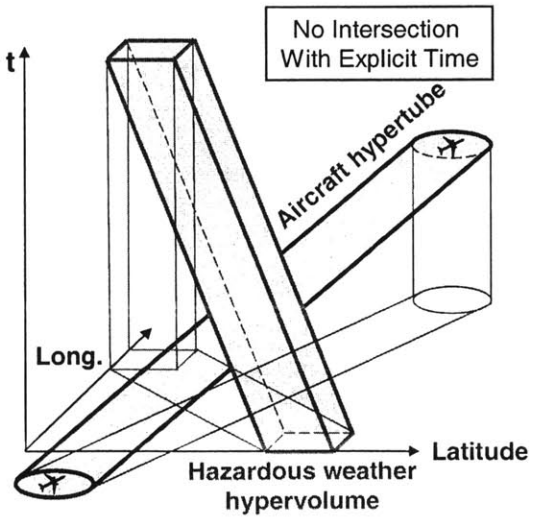


Figure 3.18: Space-time representation of four-dimensional intersection

Weather forecasts are currently assessed using the spatial reference frame such as illustrated in Figure 3.17. An abstraction of the physical problem solved by the pilot using weather information is more

appropriately represented as a four-dimensional problem using Figure 3.18. This observation is used as a basis for the framework presented next.

3.6.3 Framework of Integrated Space-Time Forecast Evaluation

The representation of time and uncertainty in weather forecasts is a key topic of research for weather information. In order to ensure the most value out of forecasts, new methods are required to assess their usability. The simple two-dimensional analysis presented here provides an illustration of the potential benefits in reducing the temporal and the spatial resolutions of a forecast provided over a time interval. Moreover, it helps identify *what* temporal and spatial resolutions should be used for various weather phenomena dynamics given some desired criteria of forecast performance. The False Alarm Ratio (FAR) is used as a metric of forecast performance throughout the analysis, but the method can be extended to other commonly used metrics including the Critical Success Index (CSI) and the Mean Square Error (MSE).

Table 3.4: Two-by-two contingency matrix

		Forecast	
		Yes	**No**
Occurrence	**Yes**	Correct Detection (CD)	Missed Detection (MD)
	No	False Alarm (FA)	Correct Rejection (CR)

The four generic contingencies for evaluating forecasts are illustrated in Table 3.4. Each contingency is traditionally evaluated by comparing the volume (or the area in the case of 2-D forecasts) of forecast and occurrence (i.e., the weather observation). Therefore a contingency such as the FA may be quantified as a volume in space for which the forecast was falsely provided. A score such as the FAR, which corresponds to the ratio of positive forecast that was wrong, may then be computed as:

$$FAR = \frac{FA}{FA + CD} \qquad \text{(Equation 1)}$$

Deterministic Case to Assess a Forecast with Limited Spatial and Temporal Resolution

This simple two-dimensional treatment provides an example of how to look at a simplified forecast-observation pair with both the traditional and the integrated space-time method. Both methods indicate that the more correspondence there is between forecast and observation, the better the scoring metric is. Using the space-time method however, a relationship between the scoring metric and the temporal

resolution of the forecast is established. Moreover, the integrated space-time method provides means to compare the influence of both the spatial and the temporal resolutions of a forecast on the score.

Figure 3.19 illustrates the case. As can be seen in the bottom left cell (cell I) of Figure 3.19, the forecast region is represented to cover some area of the x-y plane. The other three cells present a space-time representation of the problem where time is shown on the vertical axis. The top left cell (cell II) represents the forecast region and the actual adverse weather region in the space-time reference frame and identifies the characteristic parameters used to describe the problem. These are defined as:

ΔT: Forecast valid time (or forecast resolution)

w: Width of the actual adverse weather region

V: Adverse weather region displacement velocity

V.ΔT: Displacement of the actual adverse weather region over ΔT

d: Additional length covered by the forecast region

D: Total lengths of the forecast region or forecast spatial resolution

As can be seen in the figure, the total length can be expressed as a function of the other parameters as:

$$D = V_x \Delta T + w + d \qquad \text{(Equation 2)}$$

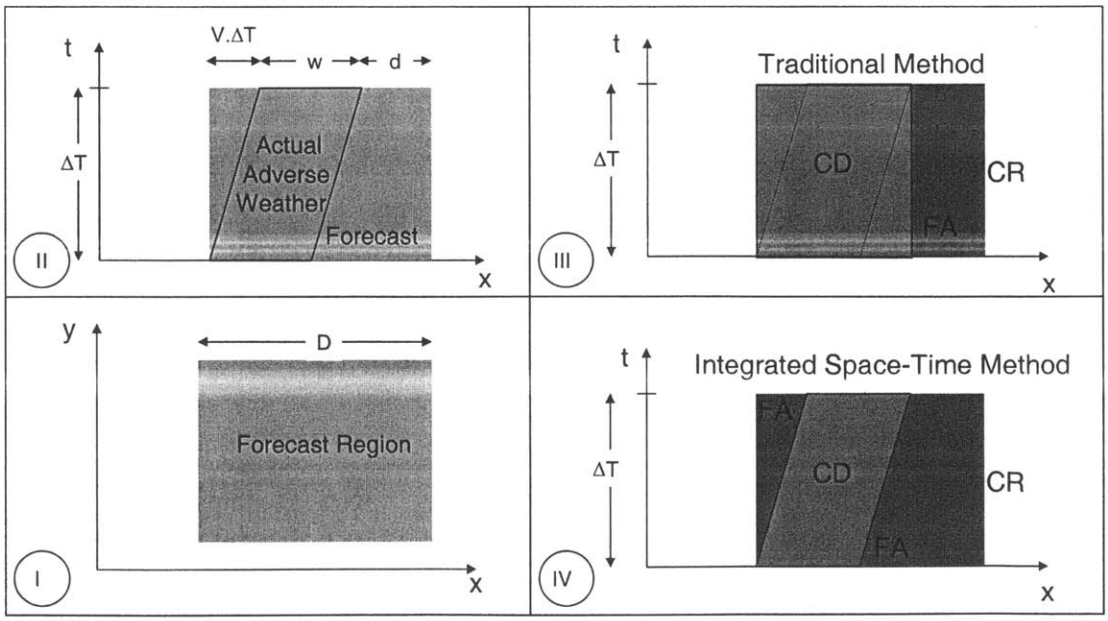


Figure 3.19: Spatial and space-time reference frames to compare forecast and observations

Spatial reference frame (bottom left) and space-time reference frames (other three)

The top right portion of Figure 3.19 illustrates how the traditional method rates the performance of the forecast by comparing it to the observation. As can be observed, the correct detection area is characterized by the points in space affected by the actual adverse weather region *at any time during the time interval.* The bottom portion of Figure 3.19 illustrates how the integrated space-time method rates the performance of the forecast. In this case, a correct detection is characterized by points in space-time where there was overlap between the forecast and the observations. The region of correct detection is smaller in the integrated space-time method than in the traditional one.

In terms of the characteristic parameters, the FAR under the integrated space-time method can be calculated as:

$$FAR = \frac{FA}{FA + CD} = \frac{V_x \Delta T + d}{V_x \Delta T + d + w} = \frac{1}{1 + \frac{w}{V_x \Delta T + d}} \qquad \text{(Equation 2)}$$

As can be identified using the equation, the FAR increases with:

- Increasing displacement velocity V of the adverse weather region
- Increasing forecast valid time ΔT (or decreasing forecast temporal resolution)
- Decreasing adverse weather region width w
- Increasing forecast spatial resolution D for the same adverse weather region width w since:

$$V_x \Delta T + d = D - w \qquad \text{(Equation 3)}$$

The formula may be transformed to look at the maximum time interval corresponding to the desirable forecast temporal resolution for a desired minimum performance score such as the FAR into:

$$\Delta T = \left(\frac{FAR}{1 - FAR} \right) \frac{w}{V} - \frac{d}{V} \qquad \text{(Equation 4)}$$

In this case, the maximum acceptable forecast valid time (and hence the minimum desirable forecast temporal resolution) is found to be influenced by:

- Decreasing FAR
- Increasing adverse weather region width w
- Decreasing displacement velocity V of the adverse weather region
- Decreasing additional length d covered by the forecast

Finally, the relationship expressed in Equation 2 may also be transformed to identify a maximum dimension corresponding to the desirable forecast spatial resolution:

$$D = \frac{w}{1 - FAR} \qquad \text{(Equation 5)}$$

The maximum acceptable length of the forecast region (and hence the minimum desirable forecast spatial resolution) is hence found to be influenced by:

- Decreasing FAR
- Increasing adverse weather region width w

An example of how these results can be used is illustrated next.

Example: Maximum Forecast Valid Time

Table 3.5 provides examples of the maximum desirable forecast valid times (or forecast temporal resolutions) for various examples of weather phenomena with a selected FAR of 20%.

Table 3.5: Examples of relevant time intervals across weather phenomena

		Characteristic Dimension D (m)	Speed of Growth/ Displacement V (kt)	Maximum Forecast Temporal Resolution ΔT
Icing	**Horizontally**	100	60	25 min
	Vertically	1	1/6	1.5 hr
Convective Weather	**Single Cell**	25	10	37 min
	Line Extension	1000	300	50 min
	Vertical Growth	3	3	15 min
	Tornado	0.01	6	1.5 sec
Volcanic Ash	**Horizontally**	100	100	15 min
Ceiling & Visibility	**Localized**	100	10	2.5 hr
	Large	1000	10	25 hr

This example illustrates how the influence of the dynamics of weather conditions can and should be captured in the generation of weather forecasts.

3.6.4 Link of Framework to Pilots' Perspective and Summary

The framework of integrated space-time forecast evaluation was presented to provide a method to evaluate the performance of forecasts in a way that better matches pilots' trajectory-centric perspective. Figure 3.20 shows aircraft trajectories in space (at the bottom of the figure) and in space-time (at the top and center). As can be seen in the space-time representations of the figure, the forecast provided a false

alarm for Aircraft B and a correct detection for Aircraft A. The traditional verification method does not capture that as the trajectories of Aircraft A and B both intersect with the traditional method's Correct Detection contingencies.

Moreover, the framework provides means to assess the influence of forecast parameters such as temporal and spatial resolution on the value of forecasts. In the framework, the value of information is expressed as a score that matches the pilot's perspective better than traditional forecast verification methods. It is also observed that the spatial and temporal resolution of forecast regions in spatio-temporal proximity to aircraft trajectories and critical trajectory points may have more value to pilots than detailed information about adverse weather regions elsewhere, especially if the pilot is able to avoid such regions altogether. The space-time representations used in the context of the framework could be used to further explore this topic in future research.

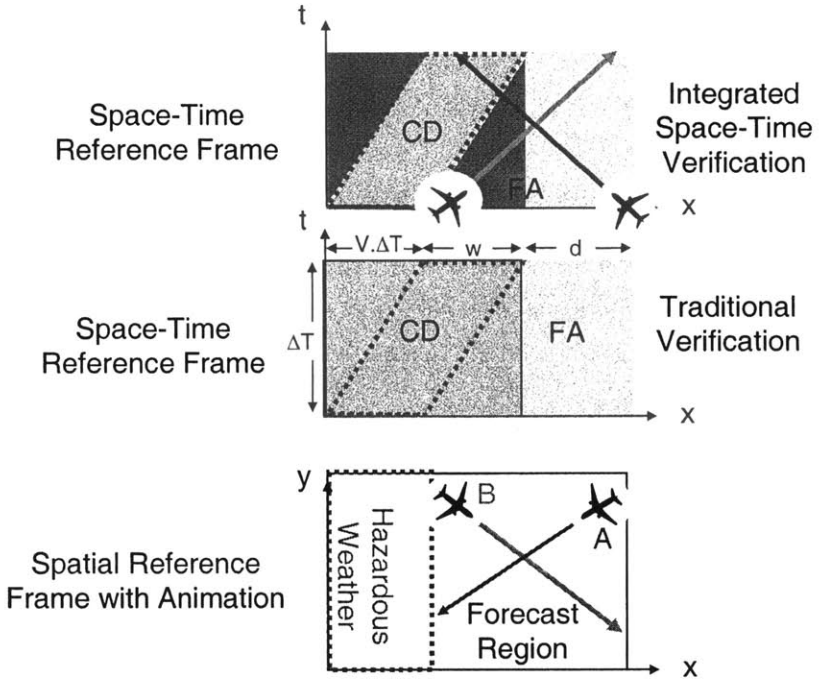


Figure 3.20: Illustration of how the integrated space-time framework matches pilots' perspective

3.7 SUMMARY

Models relevant to describing the human-controlled adverse aircraft-weather encounter problem were presented in this chapter. The models specifically focused on three domains relevant to the problem: the physical aspect of the situation dynamics, the pilot, and the information system that support the pilot in

making informed decisions and mitigating the risks of encounters. The models provided detailed insights into the key elements relevant to all three domains. In addition, two frameworks serving to link the domains relevant to the problem were developed. The framework of temporal decision-making provided a structure for evaluating aviation weather information users' planning and information use. The framework of integrated space-time forecast evaluation provided means to assess elements of the weather information system in a way that better matches pilots' perspective of the physical situation dynamics of adverse aircraft-weather encounter.

4 SCENARIO-BASED COGNITIVE WALK-THROUGH

In order to study the weather information processes from a user perspective, a scenario-based investigation of weather information needs for several adverse weather cases was conducted. This investigation serves two purposes: 1) it provides a structure to investigate pilots' decisions and use of information in a realistic setting; 2) it serves to illustrate the concepts presented in the models and frameworks of Chapter Three.

Chapter Four is divided into five sections. The first section describes the methodology that was used to conduct the scenario-based investigation. Sections 4.2 through 4.4 cover the key results of three hypothetical scenarios that were investigated based on case studies of actual adverse weather conditions, including icing, convective weather, and low ceilings and visibility. Section 4.5 summarizes the results of these investigations and the implications for improving weather information.

4.1 METHODOLOGY

The scenario-based analysis was conducted by studying specific hypothetical scenarios of aircraft-weather encounters of actual weather conditions via a *cognitive walk-through* of each scenario at meaningful time events. The concept of the cognitive walk-through is taken from the community of human-computer interaction (Wharton, 1994) to refer to a method by which an evaluator construct task scenarios and role plays the part of an operator using the weather information, "walking through" the information system. Each step of the user is scrutinized and limitations of the weather information are identified. Also, convoluted, circuitous paths through elements of weather information may be identified and indicated that the weather information needs new features that simplify the task. The weather situations used in each scenario are based on case studies of actual icing, convective weather, and low ceilings and visibility occurrences. The scenarios were selected to represent different weather hazards and flight operations for discussing aviation weather decision-making issues and are entitled:

- Scenario 1: Icing scenario for aircraft without ice protection
- Scenario 2: Frontal convective weather scenario for jet aircraft
- Scenario 3: Marginal Visual Flight Rule (VFR) conditions for non-instrument pilot

In each case, the missions and decisions of the pilots were synthesized to illustrate challenging characteristic encounters.

The weather information for the scenario-based analysis was collected from the following sources:

- The weather pages of the Aircraft Owners and Pilots' Association members' website (*www.aopa.org*), which includes links to value-added aviation weather information provided by Meteorlogix;
- The web pages of the National Weather Service Aviation Weather Center (*www.aviationweather.gov*);
- The Aviation Digital Data Service's Flight Path Tool (*adds.aviationweather.gov*), which is a product resulting from the joint effort of NOAA Forecast Systems Laboratory (FSL), NCAR Research Applications Program (RAP) and the National Center for Environmental Prediction (NCEP) Aviation Weather Center (AWC);
- The weather pages of a free flight planning website (*www.fltplan.com*), which provide a good synthesis of links to a variety of key weather providers;
- The website of the CSC Direct Users Access Terminal (*www.duats.com*), which provides access to FAA approved information for obtaining standard weather briefings
- The ceiling and visibility tool available on the NCAR website (*www.rap.ucar.edu/projects/cvis*)

In addition, a few free archive websites were also used, including:

- The National Climatic Data Center archive of surface weather observations and NEXRAD radar (*www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwNexrad~SelectedImage~20040205~1100*)
- The NCAR NEXRAD archive viewer (*www.rap.ucar.edu/staff/pneilley/NIDS_archives.html*)

In each scenario, weather information was collected for a specific case study. In the icing scenario, Scenario 1, icing information was collected between December 9 and December 11, 2003. In the convective weather scenario, Scenario 2, convective weather information was collected between February 3 and February 5, 2004. In the VFR into IMC scenario, Scenario 3, ceiling and visibility information was collected between February 4 and February 6, 2004.

4.2 SCENARIO 1: ICING CONDITIONS FOR AIRCRAFT WITHOUT ICE PROTECTION

4.2.1 Scenario Details

In Scenario 1, an instrument-rated pilot is planning an afternoon cross-country flight in the US Northeast during the late fall. The synoptic weather during that afternoon is affected by a cold front moving from the West over the area of interest and icing conditions are possible. This scenario was selected because it exemplifies decision-making with regard to potential icing conditions during the cold season in the northern United States and Canada. As will be observed, efforts are under way to improve the icing information available to pilots, but there are still opportunities and needs for improve on the state of the art.

The Mission

The mission involves flying from Norwood, Massachusetts (KOWD) to Cuyahoga County, Ohio (KCGF). These airports are about 500 nautical miles apart. The route is shown in Figure 4.2.2. The flight is planned for the afternoon of December 11, 2003 and the earliest departure time considered is 12pm.

The Equipment

The aircraft is a twin-engine Baron such as the one shown in Figure 4.2.1. It cruises at 170 knots and has an approximate no-wind range of 700 nautical miles with Instrument Flight Rules (IFR) reserves. The Baron is equipped for instrument flight but is not equipped for flight into known icing. Moreover, it is not pressurized, no supply oxygen is used and it would therefore not operate above 14,000 feet.

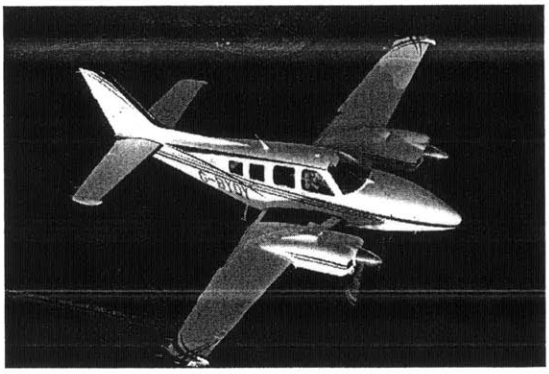


Figure 4.2.1: Example of Baron

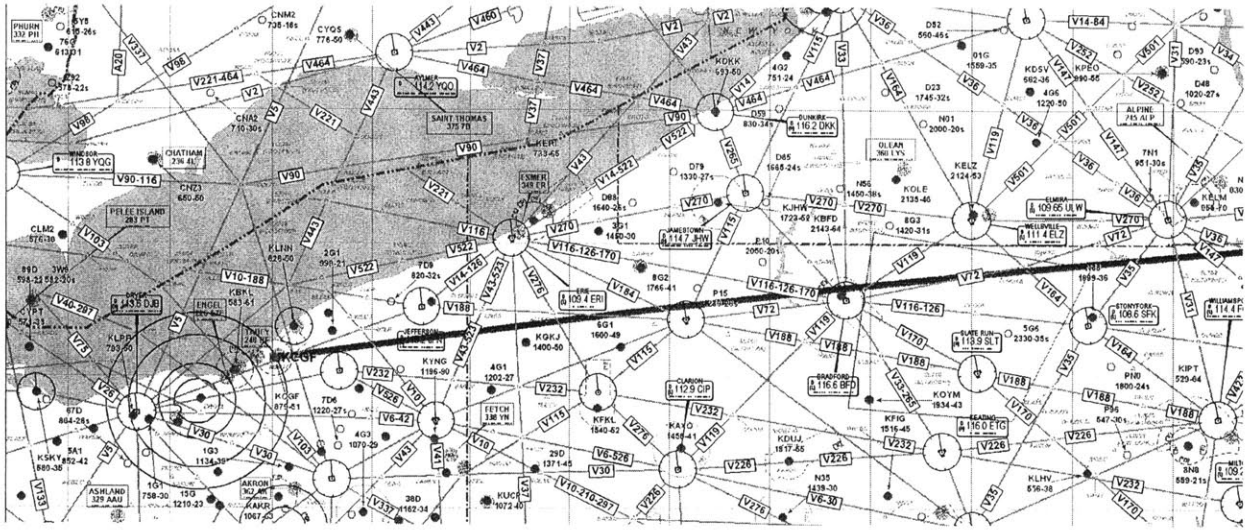


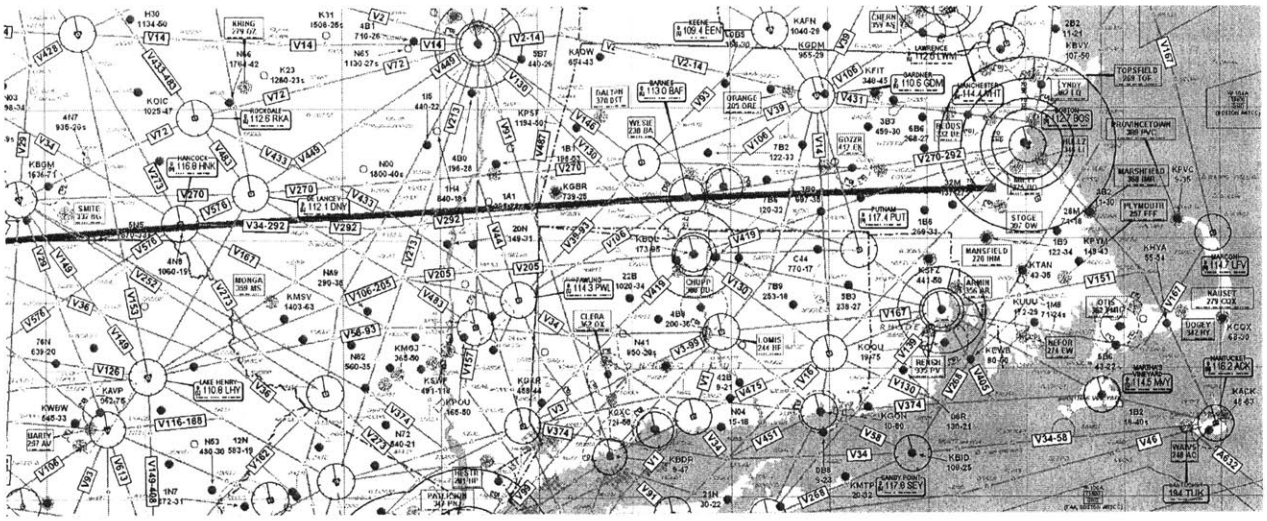
Figure 4.2.2: Nominal flight route for Scenario 1

4.2.2 Cognitive Walk-Through of Scenario 1

Two Days before the Flight (4:55pm on December 9, 2003)

In this pre-flight phase, the pilot is building a plan for her flight mission. Her plan includes a means to get from Boston to Cleveland on a Baron along a loosely defined 4-D aircraft trajectory, including an origin airport in Norwood, a destination airport in Cuyahoga County, a route of flight along Victor airways and a time window for the flight in the afternoon of December 11, 2003. Her plan also includes a model of the aircraft she wishes to use and a model of how she operates it and how proficient and current she is on the aircraft. Another important aspect of her plan is a model of the route of flight and the area where the flight will take place, including its geography, climate, airspace structure and a model of various airports and weather reporting points along her route of flight.

In order to assess whether the weather conditions may adversely affect her nominal plan, the pilot wishes to build a weather mental model (WMM). She does so by building on her prior understanding of meteorology from her theoretical background and flight experience and by consulting weather information. The information available includes the surface forecasts illustrated in Figure 4.2.3 and Figure 4.2.4, as well as information available from the media. A legend for the surface forecast is presented in Chapter Two.



(source: www.aopa.org/members)

Using the two most relevant surface forecasts that are valid a few hours prior to and after the intended flight period, the pilot identifies that adverse weather could impact her route of flight. The weather conditions she is concerned with include icing, precipitations and restricted ceilings and visibility. Her WMM includes a cold front sweeping through the area of intended flight and bringing with it considerable moisture based on the forecast precipitations. It also includes the likelihood of colder air behind the front, with a freezing level descending almost to the surface along the intended route of flight.

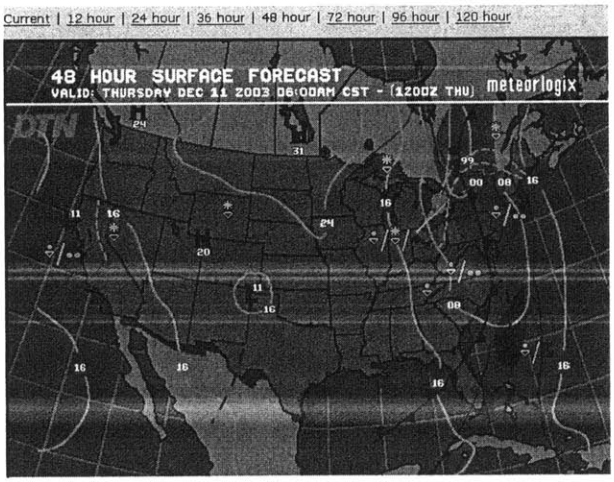


Figure 4.2.3: 48-hour surface forecast recorded at 4:55pm on December 9, 2003 (source: www.aopa.org/members)

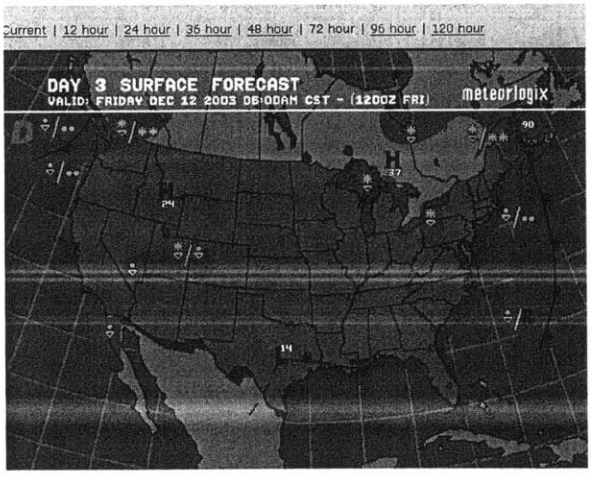


Figure 4.2.4: 72-hour surface forecast recorded at 4:55pm on December 9, 2003 (source: www.aopa.org/members)

The WMM that she builds based on this information is partly deterministic and party stochastic. Due to the length of the front and the consistency between the two forecasts about the prediction of the presence of a front sweeping through, the pilot has a deterministic representation that a front will affect her area of

flight. However, she does not have a good estimate of exactly how much moisture may come with the front. She will want to assert this with further weather information updates. In building this mental model, the pilot is informing her Level 3 situational awareness, namely her projection of the situation in the future. She will seek to validate the current WMM by looking for consistency and trends in updated and more detailed forecasts as they become available, and by seeking to validate the forecasts with relevant observations as she gets closer to her planned departure time.

Because adverse weather may affect her nominal plan to fly the Baron as planned, the pilot seeks to manage risk by evaluating alternate options and by possibly formulating contingency plans. The pilot articulates a contingency plan that involves buying a ticket on a commercial flight. If she decides to exercise that option, she assesses that it would be better to do it sooner rather than later based on her expectation that the airline ticket price would increase as she would get closer to her planned departure time. Based on her assessment of the weather, she decides to keep the contingency plan in mind but proceed with the nominal plan to fly her Baron.

Day Before the Flight (3pm and 7:30pm on December 10, 2003)

The pilot seeks to update her WMM by consulting new and updated weather information. The new surface forecasts combined with textual information from the Terminal Area Forecast (TAF) strengthen her previously developed WMM.

In order to build her Level 3 situational awareness and update her WMM, the pilot is doing four-dimensional matching between the weather information available and her planned route of flight. She needs to identify whether the TAFs are useful to her flight by identifying the locations of TAFs that are in spatial proximity to her intended route of flight and by synchronizing the TAF valid times with her planned flight time window. More specifically, she needs to identify what is the most relevant information according to its spatio-temporal proximity to the planned flight. The relevant TAFs available to the decision-maker at 3pm are included in Insert 4.1; a legend for the TAF is provided in Chapter Two.

KBOS 101808Z 101818 17005KT P6SM OVC025 TEMPO 1822 SCT025 OVC070 FM0000 16008KT P6SM OVC010 FM0300 15008KT 4SM BR OVC008 FM1000 12009KT 3SM BR OVC004 PROB30 1013 2SM -RA BR FM1300 12015KT 2SM -RA BR OVC004 FM1700 15015G25KT 1/2SM RA FG OVC002

KALB 102334Z 110024 15010G18KT P6SM BKN040 TEMPO 0003 OVC025 FM0300 15014G24KT 5SM -RA BR OVC015 TEMPO 0408 2SM RA BR OVC008 FM0800 15014G22KT 1SM RA BR OVC008 WS020/15050KT FM1500 18012KT 5SM -RA BR OVC015 FM2000 27016G32KT P6SM OVC030 TEMPO 2024 5SM -SHRA

KCLE 101737Z 101818 15012G20KT P6SM -RA SCT015 OVC035 TEMPO 1820 3SM -RA BR OVC015 FM2000 15012G18KT 5SM -RA OVC015 TEMPO 2023 2SM -RA BR OVC007 FM2300 15015KT 5SM -RA BR OVC010 FM0400 24015KT 5SM -RA BR OVC025 FM0900 27015KT 5SM -RA BR OVC025 FM1100 28015KT 5SM -RASN BR OVC015 FM1300 28020KT 5SM –SN OVC015 TEMPO 1316 2SM –SN

Insert 4.1: TAF Obtained at 3pm, December 10 2003

Figure 4.2.5 illustrates the space-time intersection that the pilot is trying to assess in evaluating the TAF. This intersection is between the relevant time windows for specific locations along the route of flight, including Boston, Albany and Cleveland, and the TAFs available at 3pm as shown in Insert 4.1. In this case, she can confirm that moisture and low ceilings are expected to affect Boston at her scheduled departure time and that icing could be a problem. However, she will have to wait for a TAF update to assess the forecast conditions along the later portion of her route.

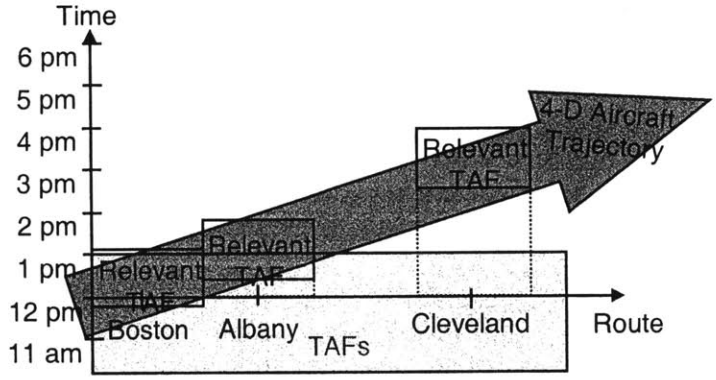


Figure 4.2.5: Representation of spatio-temporal proximity between TAFs and planned flight

Because her nominal plan includes a flight route that is likely to be affected by adverse weather, the pilot wishes to assess the availability of contingency options. In relation to icing for example, the pilot researches whether any high-confidence ice-free cruising altitudes and ice-free approach paths are likely to be available. Based on the very limited set of information available at this time, she is not able to identify any such options.

Four and a Half Hours Prior to Flight (7:30am on December 11, 2004)

In order to update her WMM, the pilot consults more updated weather information. At this point in time, she uses a variety of additional weather forecasts and observations to update her WMM. For example, using the updated TAF information, she rules out her concerns for low ceilings and visibilities. Upon

researching the likelihood for icing conditions however, she learns that it is likely to be of concern based on the mental model she builds of the "visible moisture" (i.e., clouds and precipitations, if there were any) and temperature fields.

Using the Area Forecast (FA), she confirms her assessment of the general synoptic picture with the front moving through the area of flight and builds a coarse picture of the likely cloud coverage and precipitations. She consults satellite imagery to validate the information provided by the forecasts in terms of cloud coverage. She uses the temperature information of the Winds Aloft forecast (FD) and identifies the freezing level at the various reporting points in order to estimate the boundaries of possible adverse icing areas and identify possible contingency routes. Because the freezing level is fairly low behind the cold front, she rules out any low altitude contingency routes. In addition, she confirms her expectations that icing is possible with an icing AIRMET for "moderate rime and mixed icing in clouds and precipitations", but a need to look up for pilot weather reports (PIREPs) in order to validate such expectations. No PIREPs are reported at this time of the day but the pilot also knows that the frequency of PIREPs is related to the traffic density, which is still thin at this early morning hour. In order to further validate her estimate of the likelihood for icing along her route of flight, the pilot will be seeking further PIREP information.

Because of the absence of validation elements such as PIREPs and reliable icing measurement information, the pilot's WMM still involves a stochastic representation that icing is likely along her route of flight. Because of the inability to identify any good ice-free routes, the pilot's WMM also involves a stochastic representation about the availability of ice-free areas. If her representation of both icing and her contingency options remained stochastic, she may elect no to proceed with the flight. Alternatively, she may elect to proceed if she wasn't able to develop a deterministic representation that icing would be present because of the lack of positive icing PIREPs and icing remote sensing information but if she was able to identify high-confidence contingency options (such as by developing a deterministic representation of the availability of ice-free cruising altitudes).

One and a Half Hour Prior to Flight (10:30am on December 11, 2003)

In order to make an informed go/no-go decision, the pilot updates her WMM by obtaining a standard weather briefing. Based on several icing PIREPs, the pilot transitions from a stochastic to a deterministic representation about icing conditions affecting her nominal plan. Her WMM includes a high-confidence representation that a weather system with moisture and temperatures below freezing will occur along her nominal route of flight, and that the weather system will spread along her route of flight for many miles.

The PIREPs serve to confirm the pilots' representation that this weather system is associated with icing conditions. Her representation overlaps with various temporal regimes of cognitive projection. It is partly constant because she believes that the front will remain as such for some amount of time in the future. For the later portion that affects her route of flight, she expects the front to advect while maintaining its moisture level and likelihood of icing.

In order to manage risk, the pilot wishes to investigate possible contingency plans. These could be based on cloud-free altitudes or warm altitudes (where the temperature is above freezing) where she would expect no icing conditions. However, the cloud information available with the FA refers to cloud boundaries that are exceeding her useful altitude range of up to 14,000 feet. Moreover, the freezing level is at or near the surface and hence there are no warm cruising altitudes available. No information is available regarding cloud-free altitudes or inversions aloft. Without being able to identify contingency plans, a conservative pilot would elect *not to go*.

In order to pursue the cognitive walk-through further and through the in-flight phase, the reasons why a pilot may elect to go were analyzed. Three main reasons explanations for which a pilot may elect to proceed were identified. First, due to limited icing-related training and experience, the pilot may have developed a WMM with a limited understanding of the icing phenomenology or of how the icing may influence her aircraft and operation. Alternatively, with more flexibility, she may have established a plan to proceed ahead with the flight by considering contingency plans that consist of aborting the flight and landing at the nearest airport should she encounter any ice beyond what she thinks her aircraft may handle. Finally, she may also have built a limited situational awareness by getting different information that would be less accurate due to the variability of the predictability of the weather and its chaotic nature.

Having made the decision to tentatively go ahead with the flight, the pilot develops a more detailed plan of her intentions and a more detailed four-dimensional route of flight. She files an IFR flight plan with the FSS and articulates flight details including an origin in Norwood, a destination in Cuyahoga County, an alternate destination in Cleveland, a route of flight along Victor 270, a cruising altitude at 6,000 feet, a departure time of 12pm and a time en-route of three hours. Her plan consists of a more detailed 4-D aircraft trajectory, a plan to obtain updated weather information during the flight, and an intention to divert from the flight plan should she encounter and need to maneuver around or escape from adverse weather regions.

The final weather-related cognitive activities that the pilot does before take-off include conducting a consistency check between her previously built WMM and the weather conditions she now observes with an out-the-window view of the sky at the airport as well as using the ATIS information. Using this information, she develops a contingency plan for the initial portion of her flight by establishing that the 1,300-foot broken cloud ceiling and warm temperatures will not create an icing hazard should she need to abort the flight shortly after take-off and attempt to return to Norwood. By implementing the actions of starting the aircraft engine and taking-off, the pilot is committing to her go decision and transitioning into the flight.

In-Flight Operations (12:30pm on December 11, 2003)

The pilot has taken off 30 minutes ago. In this phase of flight, the information available to the pilot includes an out-the-window view of cloud shapes and layers, the outside air temperature probe indicator and the moisture accretion rate on the windshield. She estimates that the freezing level is around 8,000 feet considering a two degree Celsius decrease in temperature for each thousand feet above her altitude. In addition, weather information is available aurally through the communication radios from the FSS, the ATIS at airports and recorded weather information at VORs in her vicinity. If the aircraft had been equipped with weather datalink, graphical and textual weather information would also be available.

Her WMM related to the remainder of her trajectory may be updated with discrepancies or corroborating factors of weather conditions in the portion of her trajectory that she observes. Examples of discrepancies includes in this scenario the differences between the solid and extensive layer of clouds forecasted versus the clear layer observed between 3,000 and 4,000 feet on the climb out of Norwood; examples of corroborating factors include the observed temperature measurement and the expected temperature field based on the temperature forecast. However, without getting an update in weather information at the remote locations further along her route of flight, she is not able to update her WMM with regard to how weather may affect the remainder of her trajectory.

Updated Weather Briefing (1:15pm on December 11, 2003)

In order to update her WMM for remote locations along her route of flight and re-Evaluate the validity of her nominal plan, the pilot seeks an update in weather information with the FSS. Based on her discussion with the FSS, she gains situational awareness that conditions are Marginal VFR and forecast to remain as such at the destination. In addition, a couple of moderate icing PIREPs has been issued at her cruising altitude 200 nm ahead. She updates her WMM with a constant representation that icing will affect her

nominal plan. Moreover, based on the weather information available, she is not able to develop a deterministic representation that ice-free contingency routes may be available ahead. In this situation, the conservative pilot would decide to adjust her nominal plan and return to her origin airport.

For a pilot with a greater tolerance to risk and/or a pilot who didn't update her WMM with the new information, there is no apparent reason not to press on with her nominal plan. The same could occur for the pilot whose WMM lacks the sophistication to help her grasp the implications of icing PIREPs through comprehension and projection of her situational awareness. While continuing the flight, the pilot is able to update her WMM about the conditions in proximity of her location. She monitors her air temperature probe as it sweeps towards -1°C at her cruising altitude. Upon considering asking for a lower altitude with ATC, she notices that her aircraft just started picking up a thin layer of ice on her windshield and wing leading edges. She now transitions from using a tactical to using a reactive planning horizon, whereas her attention is focused on escaping from the adverse icing region.

She decides to exercise a contingency plan that involves descending to a lower cruising altitude where the temperature is warmer and receives the ATC clearance to do so. Upon reaching 3,000 feet, she notices that the temperature is still below freezing and the aircraft is still picking up ice. She tunes in the ATIS for Elmira airport, builds a contingency plan with a constant representation that icing will not be an issue on the lower part of the approach there based on the 6°C ground temperature and 2,000-foot broken ceiling. She exercises her contingency plan and diverts to Elmira safely.

4.2.3 Discussion

The scenario-based cognitive walk-through presented above illustrates how the conceptual descriptive models of Chapter Three may be applied to support a better understanding of the influence of weather information on pilot decision-making. In Scenario 2 was illustrated what cognitive tasks a pilot may accomplish throughout the planning and execution of a flight. The cognitive activities of the pilot were illustrated to include building a weather mental model about icing conditions, planning, formulating a four-dimensional trajectory for a flight, using contingency plans, formulating constant, deterministic and stochastic representations of the weather conditions and their influence on her route of flight and doing consistency checks between her weather mental model and weather updates.

For reference, the timeline of decision points used in Scenario 1 is illustrated in Figure 4.2.6, where the diamond corresponds to the planned departure time. As shown in the figure, the gathering of weather information at six different time events prior to the flight was illustrated.

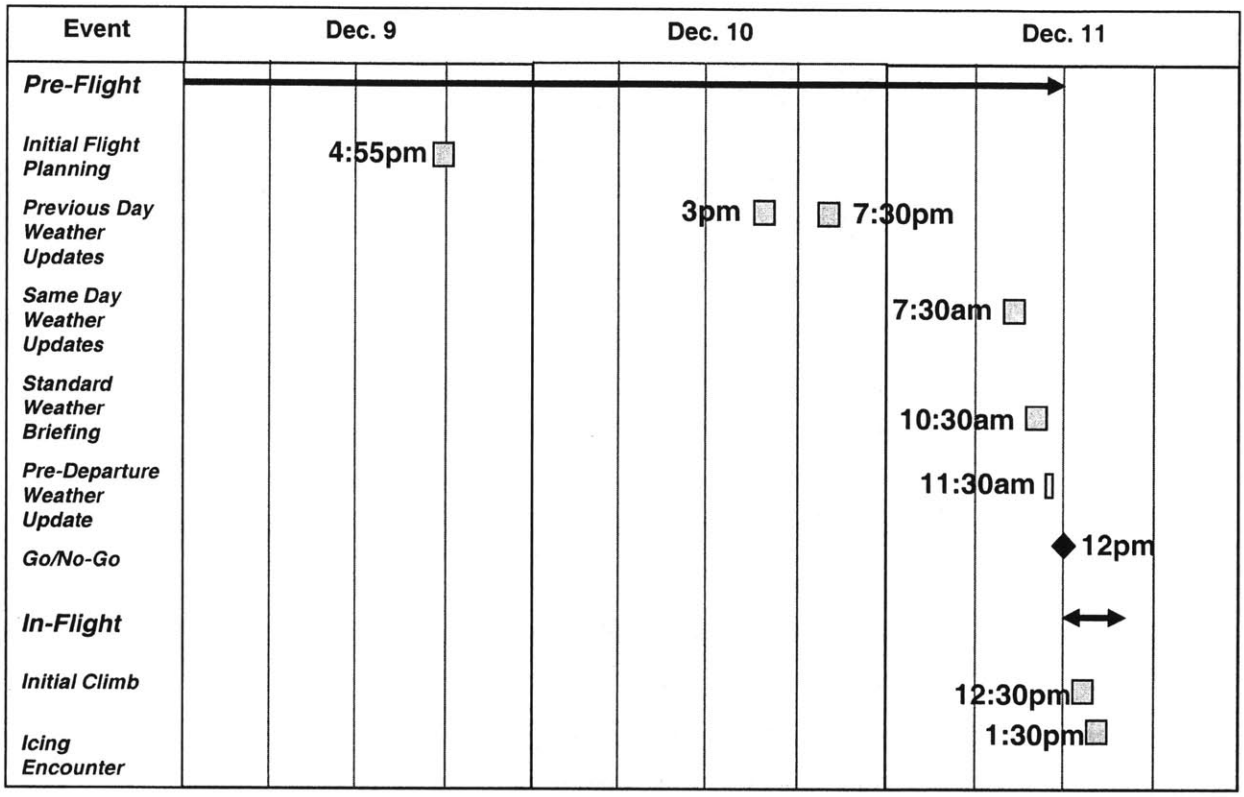


Figure 4.2.6: Gantt chart illustrating the timeline of decision points for Scenario 1

The framework of temporal decision-making introduced in Chapter Three serves to identify at a conceptual level the various planning decisions used by the pilot in Scenario 1. Figure 4.2.7 illustrates how the various decision points can be illustrated in the framework representation.

Initially, the pilot is using a stochastic representation about icing conditions affecting her nominal as well as her contingency plans in order to support strategic planning for her flight. Information collected during the initial flight planning, as well as while obtaining weather updates the day prior to and the day of the flight, indicate that there is a potential for moisture at temperatures below freezing. Therefore the pilot is expecting that icing conditions may affect her route of flight. These decision events are depicted in Figure 4.2.7 in the upper right strategic-stochastic cell for the prior days weather updates (- 1, 2 days).

Upon obtaining a standard weather briefing (-1.5 hour into the flight), the pilot learns that icing PIREPs were reported in the vicinity of the destination. Because the pilot is expecting that the conditions associated with the system are moving towards her route of flight, she expects that similar conditions could be encountered in the near future. She uses a deterministic representation of the likelihood of icing affecting her route of flight at the time when she will reach the advecting frontal area based on these positive icing PIREPs and her dynamic representation of the weather system. Moreover, it appears that the forecast cloud bases and tops, combined with the low freezing level, will leave little room for coveted ice-free cruising altitudes. Because the pilot also expects that these conditions may not significantly change in the next few hours based on the synoptic characteristics, she is also using a constant representation about the likelihood that no icing contingency routes will be available for her route of flight.

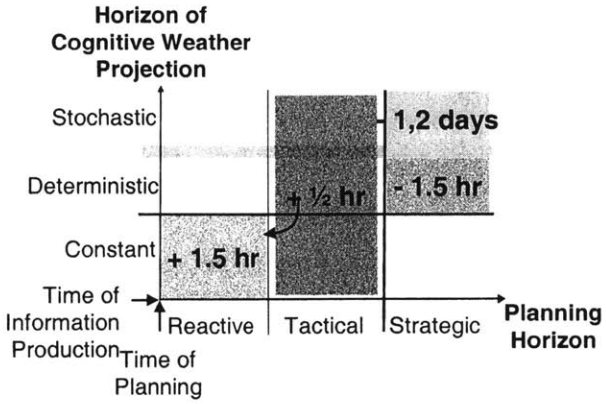


Figure 4.2.7: Framework of temporal decision-making applied to Scenario 1

Upon taking-off, the pilot transitions into a regime of flight where she may be more concerned with tactical avoidance decisions than strategic ones. The decision point taken a half hour into the flight illustrates the representation of the pilot at that time. The view out-the-window of her aircraft supports her constant representation that there is no icing in her immediate vicinity, while she has similar representations about the remainder of the flight to the one she had earlier.

Upon encountering icing conditions (+1.5 hour), the pilot transitions to a constant representation that icing affecting the immediate portion of her flight. She accomplishes tasks using a reactive planning horizon by obtaining the ATIS at Elmira. She develops a constant representation that the lower portion of the approach into Elmira is ice-free and diverts there.

4.2.4 Conclusions of Scenario 1

Scenario 1 provided a detailed illustration of how weather information is used by pilots and how this information support weather-related decision-making over time in the context of an icing scenario. It was observed that weather information was used principally to support nominal as well as contingency planning. The limitations of supporting nominal planning with the support of a stochastic representation were identified, and the value of supporting contingency planning with information that supports a deterministic representation in the context of icing was highlighted.

4.3 SCENARIO 2: FRONTAL CONVECTIVE WEATHER FOR JET AIRCRAFT

4.3.1 Scenario Details

In Scenario 2, a commercial flight crew is planning a non-scheduled flight in the Southern Mississippi Valley during an evening winter day as a line of convective weather associated with a cold front is approaching the area.

This scenario was selected because it exemplifies challenging decision-making that flight crews often have to make upon facing potential convective weather along their route of flight. Although convective weather impacts US aviation operations significantly more often during the summer months, this winter scenario serves to illustrate that decision-making related to convective weather is of interest throughout the year.

To simplify the discussion, only the captain's decision-making process is analyzed in this scenario.

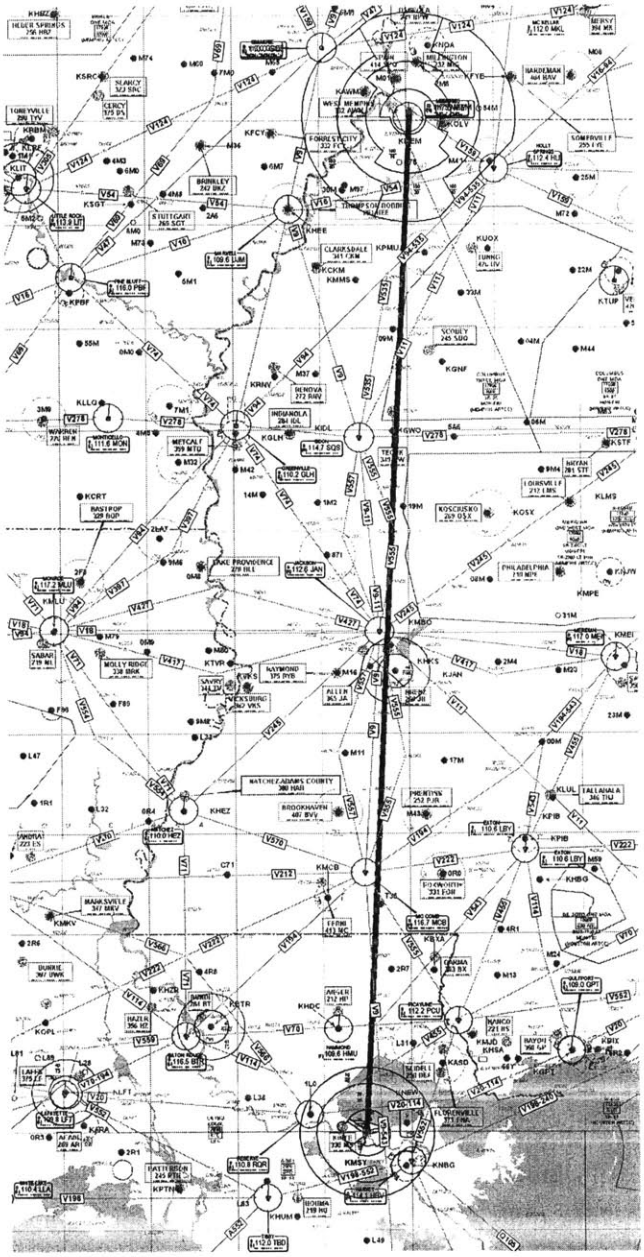


Figure 4.3.1: Nominal Flight Route for Scenario 2

The Mission

The mission involves flying from New Orleans, LA (KMSY) to Memphis, TN (KMEM), which are about 300 nautical miles apart. The route is shown in Figure 4.3.1. The flight is planned for the evening of February 5, 2004, with an earliest departure time planned for 9pm.

The Aircraft

The aircraft is a Learjet 24 such as the one shown in Figure 4.3.2. It cruises at 490 knots and has a range of 1,630 nautical miles. The Learjet is equipped with a weather radar and has a ceiling of 43,000 feet.

Figure 4.3.2: Example of Learjet 24 (Courtesy of NASA)

4.3.2 Cognitive Walk-Through of Scenario 2

Two Days before the Flight (2:45pm on February 3, 2004)

In this pre-flight phase, the captain is building a plan for his flight mission. His plan includes flying from New Orleans to Memphis in the company Learjet 24 along a four-dimensional aircraft trajectory that includes an origin airport in New Orleans, a destination airport in Memphis, a route of flight along Jet routes and a time window for the 45-minute flight in the late evening of February 5, 2004. His plan includes a cognitive representation of the aircraft to be used and a model of how he operates with the first officer he is planning to fly with. Another important aspect of his plan is a model of the route of flight and the area where the flight will take place, including its geography, climate, airspace structure and a model of various major airports and weather reporting points along their route of flight.

In order to assess whether the weather conditions may adversely affect his nominal plan, the pilot wishes to build a weather mental model (WMM). He does so by building on his prior understanding of meteorology from his theoretical background and extensive flight experience and by consulting weather information. The information available includes the surface forecasts provided on the member section of

the Aircraft Owners and Pilot Association website (*www.aopa.org*) illustrated in Figure 4.3.3 and Figure 4.3.4. A legend for these figures is included in Chapter Two. In this case, the surface forecast charts are applicable twenty-two hours prior to the planned departure time and about one hour following the planned landing time.

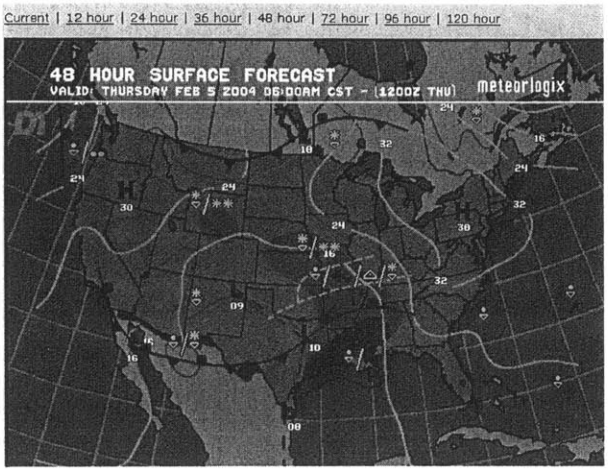


Figure 4.3.3: 48-hour surface forecast recorded at 2:45pm on February 3, 2004

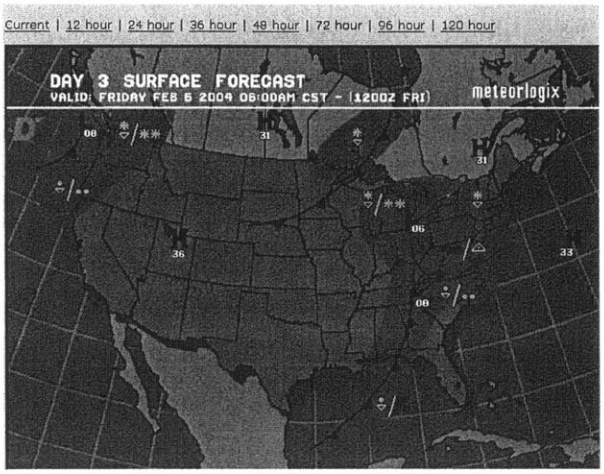


Figure 4.3.4: 3-day surface forecast recorded at 2:45pm on February 3, 2004

Using these two most relevant surface forecasts, the pilot builds a WMM of the synoptic weather situation several days in the future for the intended time of flight. His WMM includes a cold front associated with thunderstorm precipitation sweeping across their route of flight. The pilot identifies that adverse weather conditions related to convective weather, including thunderstorm, strong precipitation, hail, severe turbulence, low level wind shear, icing and potentially low ceilings and visibilities may adversely affect their mission. He doesn't have a good estimate of whether the front line will have gaps that could allow them to circum-navigates the storms and whether the storm line will be too high to prevent them from over-flying the tops. He will want to assert this with further weather information updates. The WMM that he builds based on this information is partly deterministic and partly stochastic. His expectation that the front will be present in the general area and timeframe relevant to his flight is deterministic, but his representation of the location, strength and extent of the front is stochastic. In building his WMM, the pilot is informing his Level 3 situational awareness, namely his projection of the situation in the future. He will seek to validate his current WMM by looking for consistency and trends in updated and more detailed forecasts as they become available, and by seeking to validate the forecasts with NEXRAD observations as he gets closer to the planned departure time.

Because adverse weather may affect their nominal plan to fly the planned route, the pilot seeks to manage risk by evaluating alternate options and by possibly formulating contingency plans. The pilot articulates

contingency plans that include: 1) flying over the storm line; 2) flying through sufficiently large non-convective discontinuities or gaps in the convective front line; 3) circumnavigating the front line to the South should it not extend too far; 4) advancing or delaying the flight. At this point, the pilot is unable to assess any of these options in a deterministic manner due to the large uncertainty in the weather predictability.

Day before the Flight (2pm on February 4)

The pilot seeks to update his WMM by consulting new and updated weather information. The new surface forecasts strengthen his previously developed WMM. No TAF or other convective weather forecasts are available to support further assessments of the nominal and the contingency plans.

Day of the flight (9:10am and 2:08pm on February 5)

In order to update his WMM, the pilot consults more updated weather information. Textual weather forecasts become applicable to the intended flight period, including Area Forecasts (FAs) valid for 12 hours and Terminal Area Forecasts valid for 24 hours. In addition, graphical information including Low Level Significant Weather Charts (shown in Figure 4.3.5) and a radar summary chart start to show features of the frontal line that are relevant for planning their departure 13 hours later. Also, the updated surface forecast charts matches the previous forecasts.

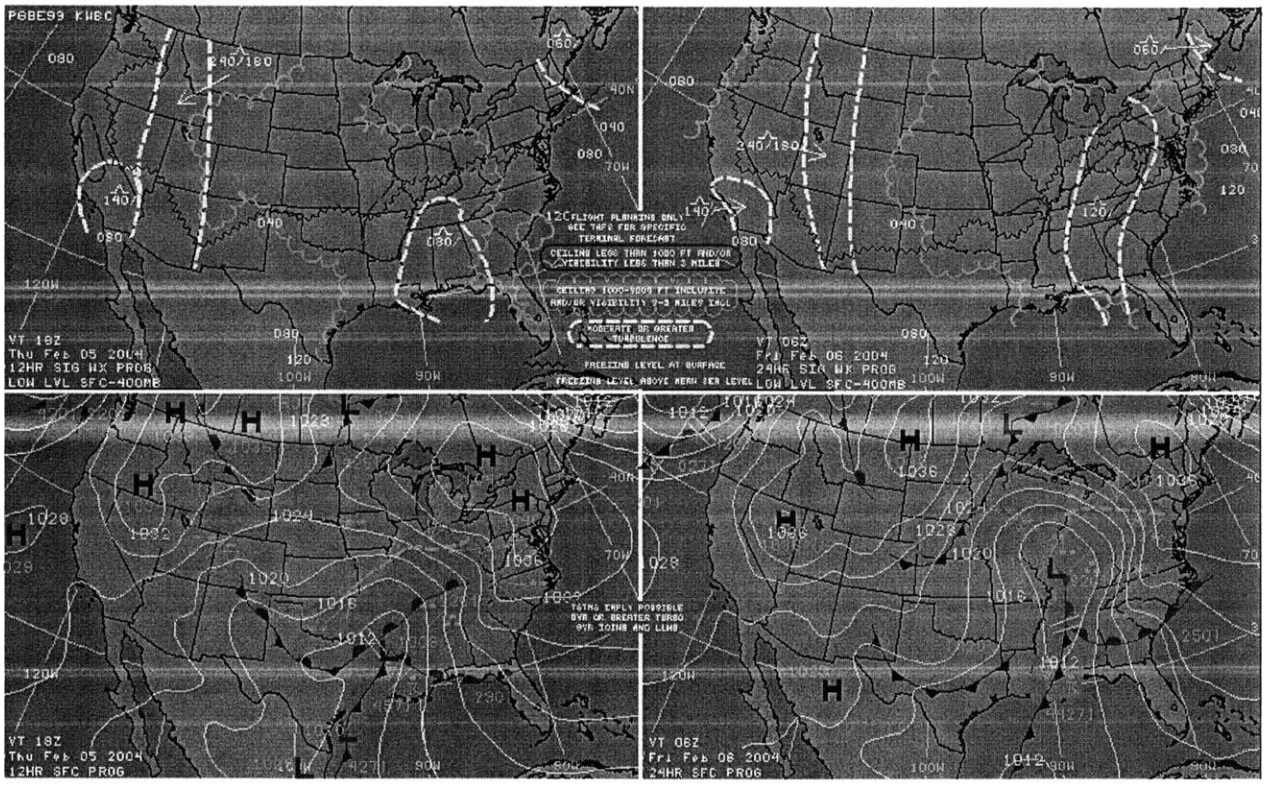


Figure 4.3.5: Low Level Significant Weather Chart at 10:10am on Feb. 5, 2004

Using the graphical information of Figure 4.3.5 combined with the textual information, the pilot updates his WMM about the potential influence of the storm line on his planned route of flight. He is now more confident that storms at the cold front will affect his route of flight. He now expects that the front line will likely intersect their route but will not have reached their origin in New Orleans and will have cleared their destination in Memphis during the planned flight time. In addition, he is able to identify that low IFR conditions will not pose a problem to their flight based on 1,000-foot forecast ceilings in New Orleans and Memphis for the planned flight time.

Using the Radar Summary Chart of Figure 4.3.6, the pilot validates his WMM with "observable" convective weather and builds a deterministic representation that convective weather will affect their route of flight but a stochastic representation of how it will affect the route. He examines the Chart to identify whether there appears to be gaps in the front line and how high the echo tops are in order to support his contingency planning. He concludes that it is possible for the aircraft to "top" the ridge at its present state without significant deviation from the planned route, but that the storms are likely to grow during the day because of expected surface heating. He will plan to update these assessments with further weather information updates.

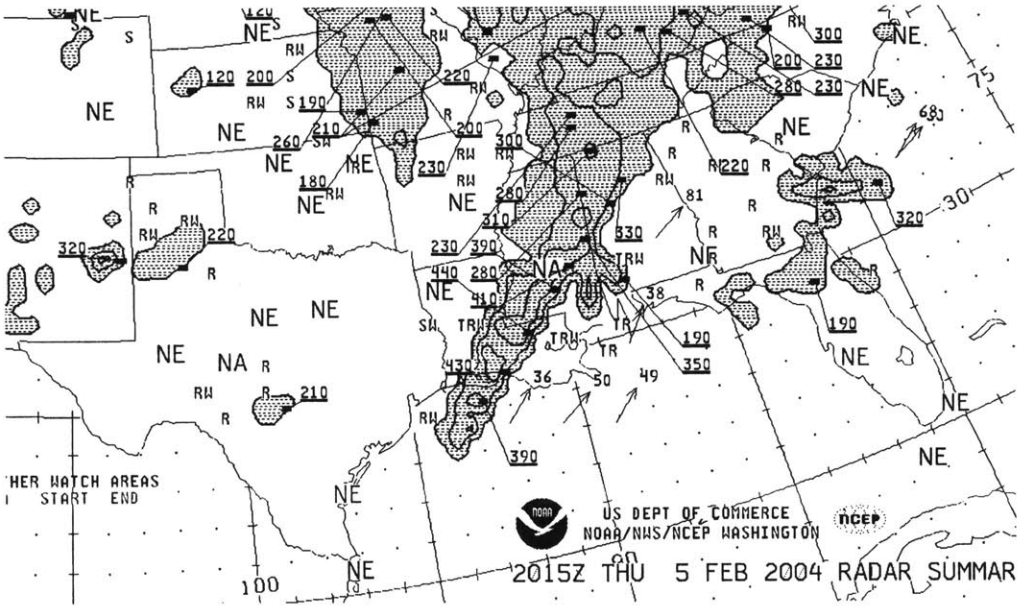


Figure 4.3.6: Radar Summary Chart Recorded at 2:18pm on February 5

One Hour Prior to Flight (8pm on February 5, 2004)

In order to make an informed Go/No-Go decision and select appropriate resources and route of flight, the pilot updates his WMM by using a weather information terminal at a New Orleans Fixed Base Operator (FBO) and by obtaining a standard weather briefing from the FSS.

In order to update and validate his WMM, the pilot consults the NEXRAD mosaic and surface analysis shown in Figure 4.3.7 and the 12-hour surface forecast chart show in Figure 4.3.8. Using an animation loop of the radar mosaic, he builds a model of the intensity, the configuration and the dynamics of the line storm. In addition, as part of his route planning, he identifies a route that will allow him to circum-navigate and avoid the storm line altogether using the NEXRAD animation loop.

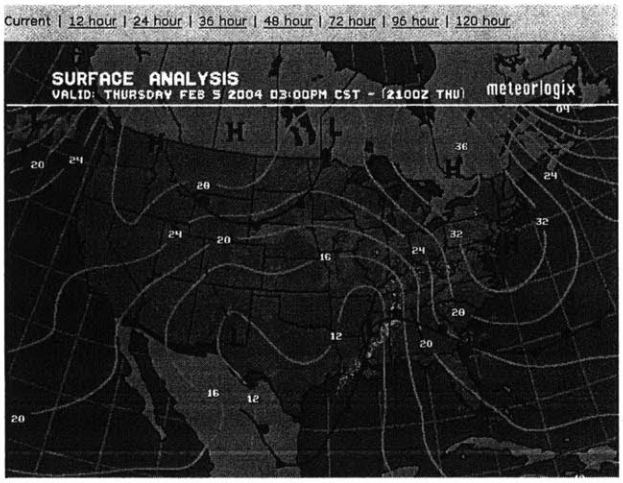


Figure 4.3.7: Surface analysis recorded at 8:00 pm on February 5, 2004

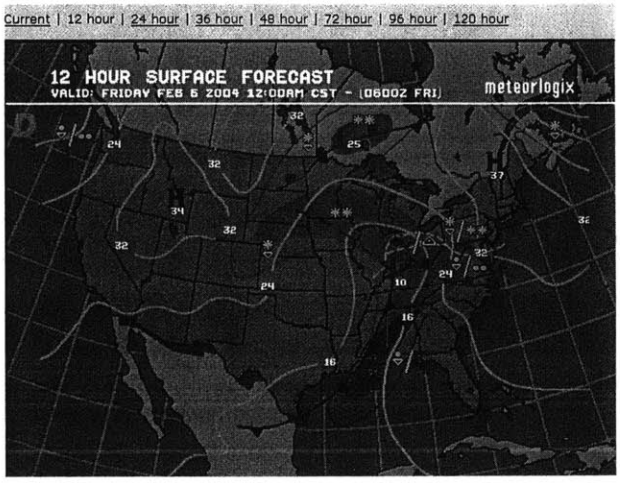


Figure 4.3.8: 12-hour surface forecast recorded at 8:00 pm on February 5,2004

The pilot obtains a standard weather briefing and files an IFR flight plan. Based on the Area Forecast, the pilot develops a stochastic representation of the volume of airspace that he expects the storms will occupy, with tops decreasing from 43,000 feet down to 34,000 feet after 8pm in the Southern portion of the planned route, and extending up to 37,000 feet in the northern portion of the route. He also builds a stochastic representation that contingency options such as over-flying the echo tops will be possible.

The pilot is not able to get a good estimate about the location of the Convective SIGMET (illustrated in Insert 4.2) with respect to his route of flight without pulling out a map since he is not familiar with the Choo-Choo and Lake Charles VOR.

Convective SIGMET valid until 10:55pm EST: For Tennessee, Alabama, Mississippi, Louisiana, and Louisiana, coastal waters From 20 miles south-southeast of Nashville TN [BNA] to 50 miles south-southwest of Choo Choo [GQO VOR] to 90 miles south-southeast of Lake Charles LA [LCH] to 90 miles south-southwest of Lake Charles LA [LCH] to 20 miles south-southeast of Nashville TN [BNA] Area severe embedded thunderstorm(s) moving from 270 at 10 knots. Tops to flight level 410. Tornadoes ... hail to 1 inch ... wind gusts to 60 knots possible. Outlook valid the 6th at 12:55am EST (0755Z): From Nashville TN [BNA] to Foothills [ODF VOR] to 80 miles southeast of Leeville [LEV VOR] to 120 miles south-southwest of Lake Charles LA [LCH] to Nashville TN [BNA]. Convective SIGMET issuances expected.

Insert 4.2: Convective SIGMET obtained at 8pm on February 5, 2004

While still on the phone with the FSS, the pilot files a flight plan. He has decided that he would file a route that circumnavigates the frontal system to the South at a cruising altitude of 43,000 feet, and that he would carry sufficient fuel to fly that route. He made this decision based his deterministic representation that this route will be clear of convective weather and that it can be explicitly specified to ATC. However, he is planning to deviate from his filed route when he will be able to obtain a deterministic representation of a more direct route of flight with information updates and when he will be able to communicate it simply to ATC by requesting a heading change.

Going back to the weather information terminal, the pilot turns to the graphical AIRMET picture of Figure 4.3.9 and is now able to confirm what he expected with regard to the location of the convective front over the next few hours.

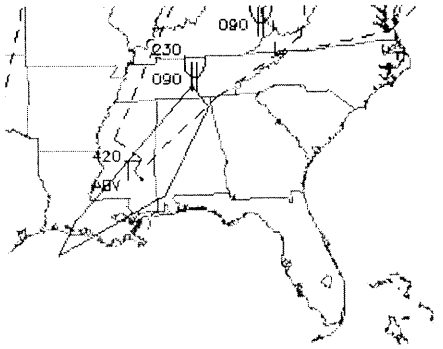


Figure 4.3.9: Graphical convective SIGMET in effect for the area of flight (depicted by the solid line)

In-Flight Weather Update (10:15 pm on February 5, 2004)

Upon reaching the top of the climb to the Southeast as filed, the aircraft emerges from the cloud deck and the pilots are able to observe the tops of the cumulonimbus line. The captain identifies a sufficiently large gap in the storm line and requests a deviation towards it with ATC. After deviating, he is able to validate and complement his WMM with the airborne radar information about the configuration and intensity of the storm. He fine-tunes his heading requests with ATC by comparing the planned heading with the graphical convective weather cells using a display such as the one showed in Figure 4.3.10.

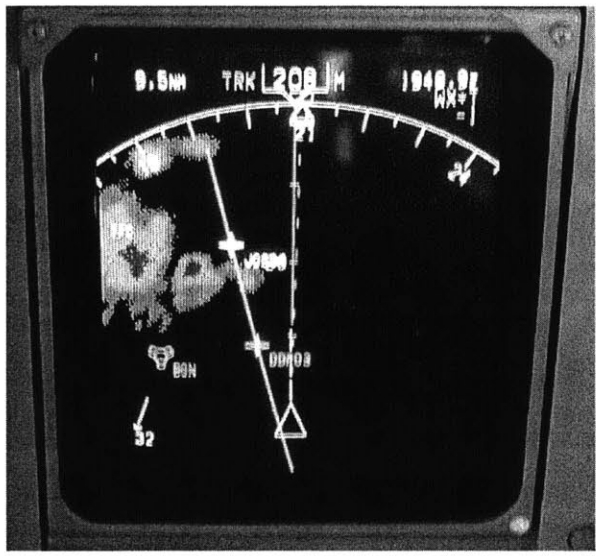


Figure 4.3.10: Example of airborne weather radar information (Courtesy of A.H. Midkiff)

Because the pilot expects potential adverse wind shear and turbulence several miles outside the storm cells, he uses a separation buffer between the convective weather regions and his planned route. Operational procedures typically define this buffer to be a few thousands of feet above convective cells and twenty nautical miles to the side of storms (FAA, 2003). On top of the cloud deck, the pilot is able to visually identify convective cells that extend beyond his cruising altitude that he wishes to avoid. Figure 4.3.11 and Figure 4.3.12 illustrate views out of the aircraft windows upon approaching the storm cell depicted in Figure 4.3.10.

Figure 4.3.11: Example of view out-the-window upon approaching a storm cell top

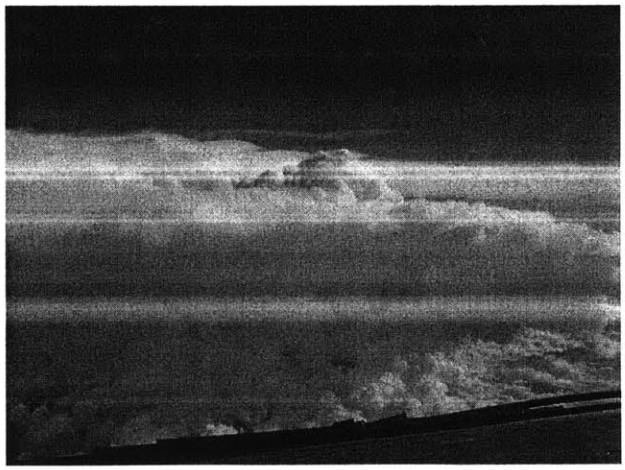


Figure 4.3.12: Example of view out-the-window upon circumnavigating a storm cell top

Based on information from both the airborne weather radar and out-the-window view of storms when outside the cloud deck, the pilot uses a constant representation of the location of the boundaries of adverse

convective weather regions to support his WMM. This WMM is limited to the regions of space that are visible from the out-the-window view and using the airborne weather radar and usually do not extend to the airspace where the remainder of the flight is. Therefore, this information does not usually support strategic planning and the WMM for further segments of the four-dimensional aircraft trajectory. During operations, the pilot therefore mostly uses this constant representation to support reactive and tactical planning decisions and to develop route plans that avoid adverse convective weather regions.

If the pilot had access to cockpit weather datalink, a more complete picture of the adverse convective weather field for the remainder of the flight would have been available. Figure 4.3.13 provides a NEXRAD image of the storm line recorded during the flight. The pilot may use either a constant or a deterministic representation of the adverse convective weather field using this information over a temporal horizon of a couple of hours. Such cockpit weather datalink graphics are not intended to support a constant representation of the adverse convective weather field because they are synthesized based on radar mosaic that may have coarse resolution in the vicinity of the aircraft.

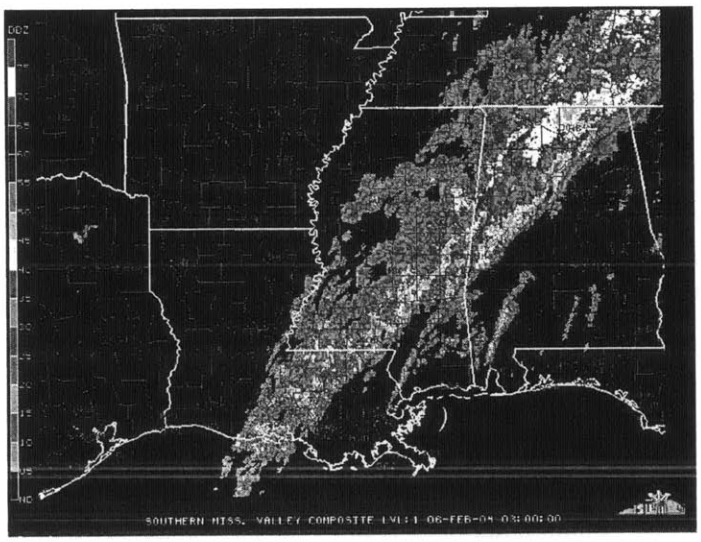


Figure 4.3.13: NEXRAD image recorded at 10pm on February 5, 2004

4.3.3 Discussion

The scenario-based cognitive walk-through presented above illustrates the planning and execution of a flight around convective weather. For reference, the timeline of decision points used in Scenario 2 is illustrated in Figure 4.3.14 where the diamond shows the planned departure time at 9pm on February 5. Five times of decision and information use were illustrated in Scenario 2.

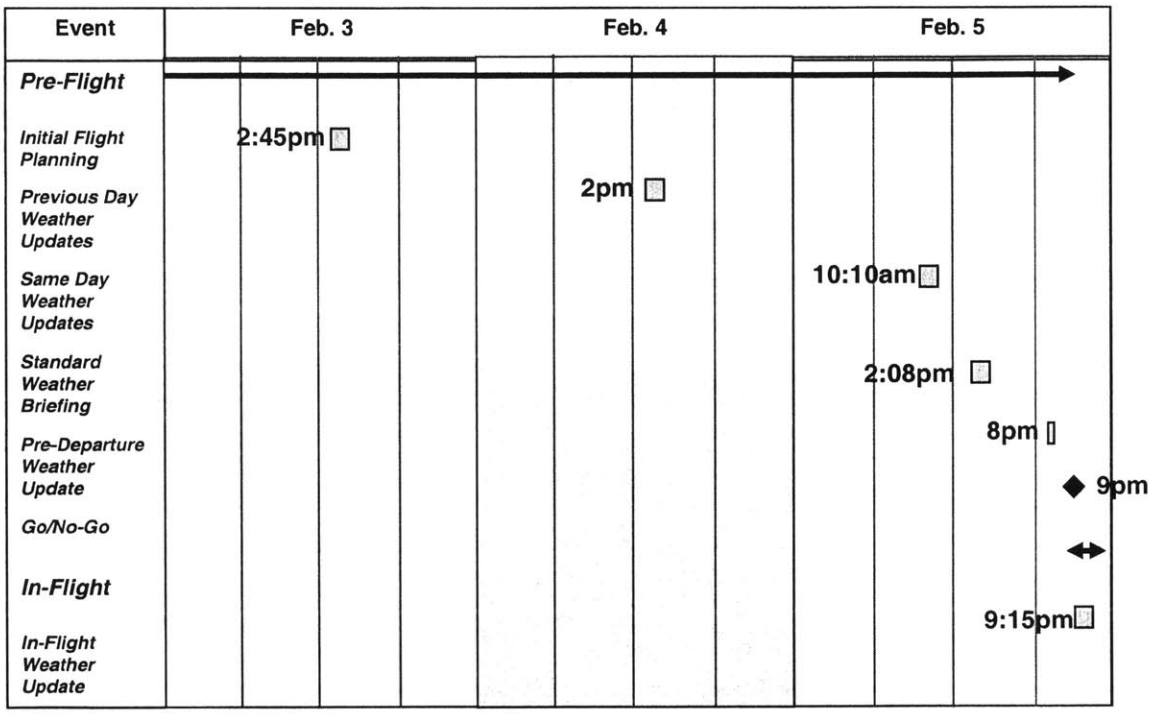


Figure 4.3.14: Gantt chart illustrating the timeline of decision points for Scenario 2

The framework of temporal decision-making introduced in Chapter Three can serve to identify at a conceptual level the various planning horizons used by the pilot in Scenario 2, as shown in Figure 4.3.15.

Initially (-1, 2 days), the pilot is using a weather mental that is partly deterministic and partly stochastic. He expects that a front will generally be present in the area and at the time of his planned flight and uses a deterministic representation about the presence of the convective weather. He also is not sure what will be the extent and dynamics of the front and how the convective weather will precisely impact his route of flight. In order to support his contingency plans early on, he sought information that would help him identify whether the convective weather region would block his access to his critical trajectory points, and whether there would be means to avoid the front by either circum-navigating it or else flying above it.

Without such information, the pilot expected to obtain weather information updates in flight and use tactical plans during the execution of his flight.

Upon taking-off (or + 15 min. into the flight), the pilot transitioned into the tactical planning regime. Two types of information provide him with means to update his weather mental model and identify a constant representation of the convective weather relevant to his route of flight: his out-the-window view of the storm cells and his airborne weather radar which provides a wider coverage of the area of flight. If the pilot had flown at night and without airborne weather radar or strike finder, he may have been able to further develop a representation of how to avoid the convective weather cell with the help of ATC but would not have as clear a cognitive representation.

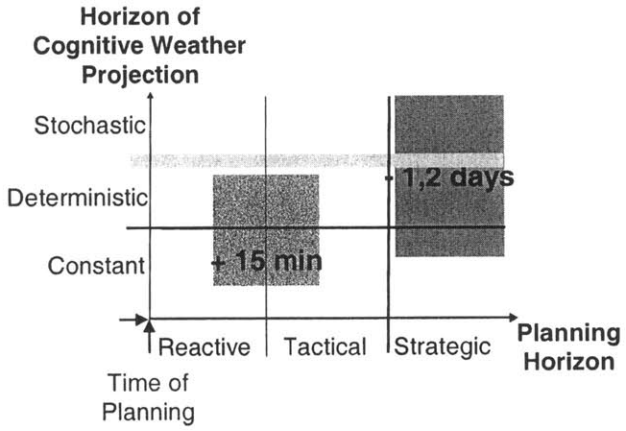


Figure 4.3.15: Framework of temporal decision-making applied to Scenario 2

4.3.4 Conclusions of Scenario 2

Scenario 2 provided a detailed illustration of how weather information is used by pilots and how this information support weather-related decision-making over time in the context of a convective weather scenario. It was observed that weather information was used principally to support nominal as well as contingency planning. The need for weather information to support the identification of four-dimensional intersection between aircraft and adverse weather regions were identified with the currently available information tools. In addition, the value of supporting contingency planning based on four-dimensional information was also identified.

4.4 SCENARIO 3: MARGINAL VFR CONDITIONS FOR NON-INSTRUMENT PILOT

4.4.1 Scenario Details

In Scenario 3, a non-instrument-rated pilot is planning a morning flight in Florida where the conditions that deteriorate into low ceilings and visibilities. This scenario was selected because it exemplifies the common challenging decision-making that non-instrument rated pilots often have to make in order to plan a flight in conditions that may involve ceiling and visibility conditions incompatible with their experience and qualifications.

The Mission

The mission involves flying under Visual Flight Rules (VFR) from Fort Lauderdale (KFLL) to Jacksonville, Florida (KJAX), which are just over 450 nautical miles apart. The flight is planned for the morning of February 6, 2003, with an earliest departure considered for 10am. The route of flight is shown in Figure 4.4.1*: Nominal Flight Route for Scenario 3.*

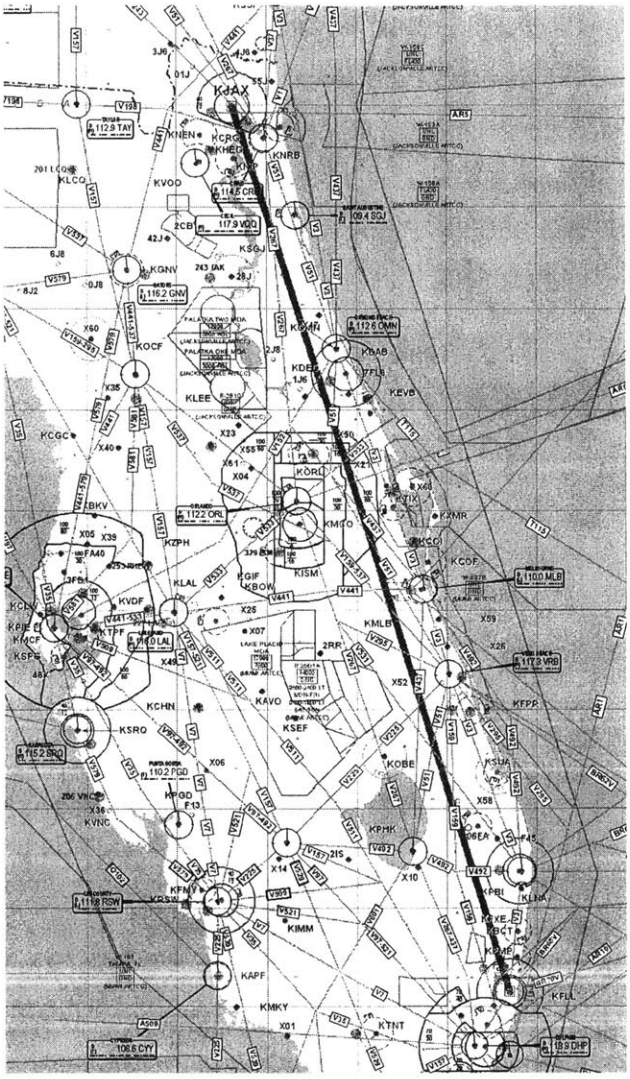


Figure 4.4.1: Nominal Flight Route for Scenario 3

The Equipment

The aircraft is a single-engine Bonanza V35A such as the one shown in Figure 4.4.2. It cruises at 170 knots, has a range of 700 nautical miles and is not equipped nor certified for flight into Instrument Meteorological Conditions (IMC). Moreover, it is non-pressurized, no supplemental oxygen is used and therefore the aircraft would not cruise higher than 14,000 feet.

Figure 4.4.2: Example of a Beechcraft Bonanza (courtesy of W.D. Hall)

4.4.2 Cognitive Walk-Through of Scenario 3

Two Days before the Flight (8:15pm, February 4, 2004)

In this pre-flight phase, the pilot is building a plan for his flight mission. His plan includes a means to get from Fort Lauderdale to Jacksonville in a Bonanza along a loosely defined 4-D aircraft trajectory, including an origin and destination airport, a route of flight on Victor airways along the West coast of Florida in the morning of February 6, 2004. His plan also includes a model of the aircraft he will use and his intent to fly under VFR. The pilot has a mental model of the route of flight and the area where the flight will take place, including its flat coastal geography, warm climate, airspace structure including the Victor airways along the coast that avoid the Bravo airspaces around Orlando and a model of various airports and weather reporting points along the route of flight.

In order to assess whether the weather conditions may adversely affect his nominal plan, the pilot wishes to build a Weather Mental Model (WMM). He does so by building on his prior understanding of meteorology from his flight lessons and his limited experience and by consulting weather information. The information available to him at this point includes the surface forecasts illustrated in Figure 4.4.3 and Figure 4.4.4. A legend for the figures is provided in Chapter Two.

Using this information, the pilot builds a mental model of the synoptic weather situation several days in the future for the intended time of flight. His WMM includes a cold front approaching the area of flight that shouldn't affect the flight if the pilot is able to leave as planned. The pilot is particularly interested in information that would help him identify whether ceilings and visibility will pose a problem for his flight, but he is not able to do that with the information available. He will seek further weather information updates.

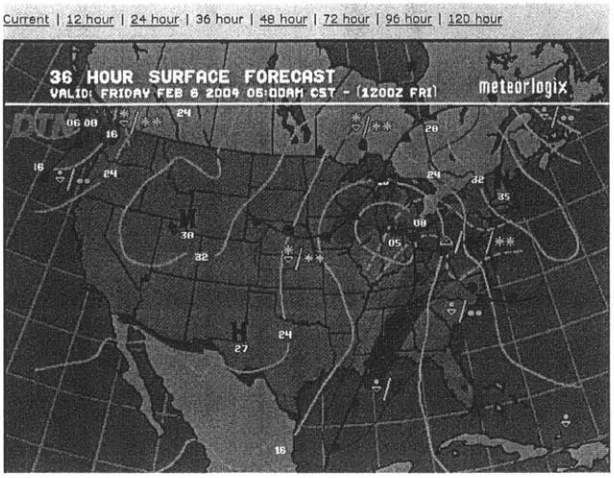


Figure 4.4.3: 36-Hour Surface Forecast Recorded at 8:15 pm on February 4, 2004

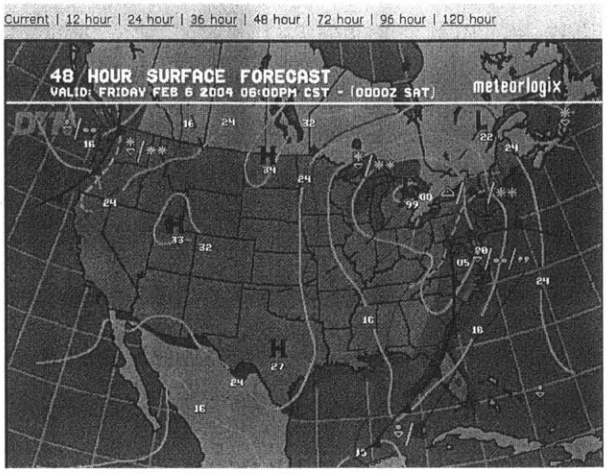


Figure 4.4.4: 48-Hour Surface Forecast Recorded at 8:15 pm on February 4,2004

Day before the Flight (10:10am and 9pm, February 5, 2004)

The pilot seeks to update his yet incomplete WMM by consulting new and updated weather information. During a morning update, the only forecast applicable to the intended time of flight is the Low Level Significant Prognostic Chart. The applicable portion for ceiling and visibilities, the Significant Weather Prognostic Chart, is shown in Figure 4.4.5. Using it, the pilot builds an expectation that the ceilings and visibilities during his planned flight time window may not be favourable to his VFR flight as they may be lower than 1,000 feet over the Florida peninsula.

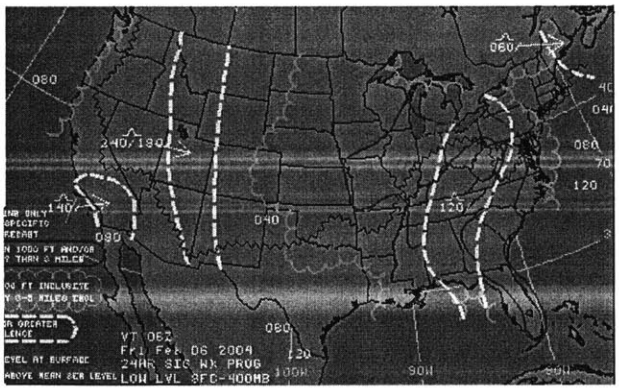


Figure 4.4.5: 24-hour Significant Weather Prognostic Chart available at 10:10am on Feb. 5 and applicable at 1am on Feb. 6

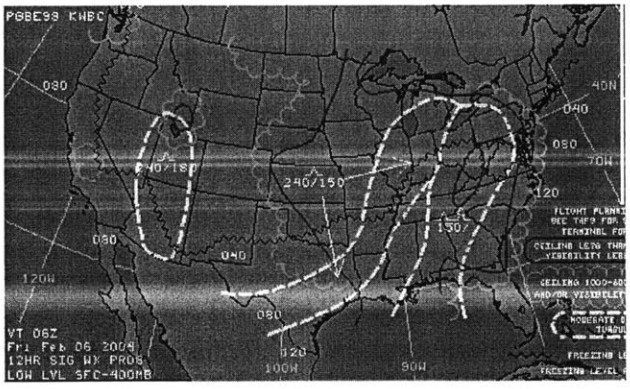


Figure 4.4.6: 12-hour Significant Weather Prognostic Chart available at 9pm on Feb. 5 and applicable at 7am on Feb. 6

A variety of weather forecasts become applicable to the intended period of flight in the evening. They include Low Level Significant Weather Charts, Area Forecast (FAs) and Terminal Area Forecasts (TAFs). Using the updated Significant Weather Prognostic Chart shown in Figure 4.4.6, the pilot reverts

his expectation and now expects VMC conditions over most of his route of flight and Marginal VFR conditions in the northern part of the route.

Using the FAs and TAFS, the pilot also includes in his WMM a model of the overnight fog predicted to dissipate and lift with diurnal surface heating. He also expects based on previous experience that a layer of high-altitude cirrus clouds could obscure the surface and prevent surface heating, which may in turn delay the fog lifting. If that occurred, it is possible that the weather would not have time to become VFR until the cold front moves through from the West and affect the northern portion of his route. Because of the change in graphical prediction between his morning and evening weather updates, the pilot also has limited confidence in the information available to him so far and will seek to further validate his current WMM with further weather information updates.

Because of the uncertainty he has in the cloud ceiling and visibility prediction, the pilot uses a stochastic representation of the impact of ceiling and visibility on his nominal plan. He will seek to update his WMM with further weather information updates.

One Hour Prior to Flight (9am, 02/06/04)

In order to update his WMM and make an informed Go/No-Go decision, the pilot obtains a standard weather briefing using the DUAT system and complements it using graphical information available on the members' section of the AOPA website. The pilots' WMM includes a model of the cloud coverage and visibility that is predicted to improve one hour into his flight at 11am with mist and rain that is expected to dissipate and with higher ceilings and visibility in the northern part of his route.

In order to build his Level 3 Situational Awareness and update his WMM, the pilot is doing four-dimensional matching between his aircraft trajectory and the predicted weather conditions. He needs to identify the locations of the TAFs that are in spatial proximity to his intended route of flight and mentally synchronize the relevant TAF valid times to his planned flight time window. More specifically, he identifies that during the time when he is planning to be in the Fort Lauderdale area, the conditions should be Marginal VFR. Upon reaching the second portion of his route, the pilot expects VFR conditions with clouds scattered at 2,500 feet.

The pilot considers contingency planning options that include aborting the flight to land at an airport along the route of flight should the conditions be worse than predicted. Because the forecast ceiling is low however, he is planning to cruise at the low altitude of 2,000 feet above the terrain, a condition that he

normally tries to avoid in order to have contingency options for having more time to glide into a landing site in the event of an engine failure.

In order to further support his WMM, the pilot consults graphical ceiling and visibility information, including the NCAR Ceiling and Visibility tool shown in Figure 4.4.7 and the ADDS Flight Path Tool shown in Figure 4.4.8. The pilot's first impression is that the two figures are providing conflicting information since Figure 4.4.7 shows VFR conditions along his route of flight and Figure 4.4.8 shows very high relative humidity that the pilot typically associates with clouds. Seeking to validate whether the information he has is correct, he cognitively compares both predictions to the information he obtained from surface observations at various airports along the route of flight. In doing so, he notices that the temperature and dewpoint spread in the METARs is very small and less than a degree Celsius for airports in the first portion of the route. Finally satisfied that he is well informed about the weather conditions and that his nominal route is clear of IFR conditions, the pilots tentatively elects to depart.

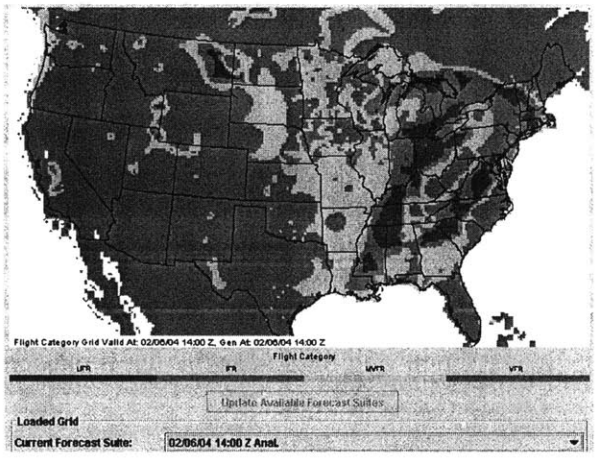


Figure 4.4.7: NCAR ceiling and visibility product valid at 9am on February 6

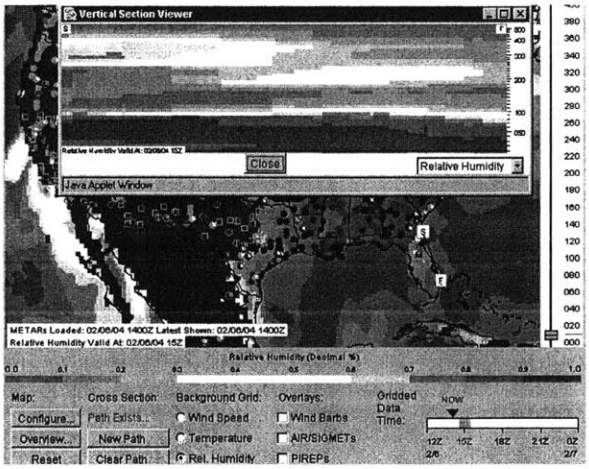


Figure 4.4.8: ADDS Flight Path Tool forecast valid at 10am on February 6 (source: adds.aviationweather.gov/flight_path)

At the airport, the pilot updates his WMM with the weather conditions he observes. He guesses that the clouds are scattered at 2,000 feet and confirms his guess with the ATIS information. He evaluates that the visibility is 10 miles and therefore not a factor for the initial part of his flight. The information he observes serves to validate and strengthen his WMM for the initial part of the route. He uses a constant representation of the conditions at his current location but has a stochastic representation that VFR conditions are likely present further along his route of flight. The pilot makes a go decision by starting the engine and taking-off as filed.

In-Flight Weather Update (11:30am, 02/06/04)

Half an hour into the flight, the pilot realizes that the cloud cover is getting more extensive than he expected, and he estimates the visibility has reduced to about five miles. The boundaries of clouds are fading away in the distance, the cloud bases vary in altitude, and he is not confident that he can pick out clouds with sufficient distance from them to circum-navigate them altogether. His flying task is demanding as he is making some heading changes in order to fly in regions of greater visibility, using a tactical planning horizon. He updates his WMM in the vicinity of his location and he now expects that the conditions may be worse than predicted further along his route of flight.

Upon entering a cloud and losing reference to the horizon, the pilot finally decides to reverse course. He updates his plan and decides to promptly find an airport to divert to. Using the VFR chart, he identifies and tunes in the ATIS frequency for an airport less than 10 miles away, Fort Pierce (KFPR), which reports 4,000 feet overcast with 2 miles of visibility and moderate rain. Deciding to rule out such contingency option on the basis that the visibility is not favourable for conducting an approach there, he tunes in the ATIS for Fort Lauderdale and elects to fly back there due to more favourable reports and since it is not too distant from the current position.

4.4.3 Discussion

The cognitive walk-through presented above illustrated the planning and execution of a flight in restricted ceilings and visibilities for a pilot who is not qualified for instrument flying. For reference, the timeline of decision points used in Scenario 3 are illustrated in Figure 4.4.9, where the diamond represents the planned departure time at 10am on February 6, 2003. As shown in the figure, weather information was obtained at four different time events prior to the flight.

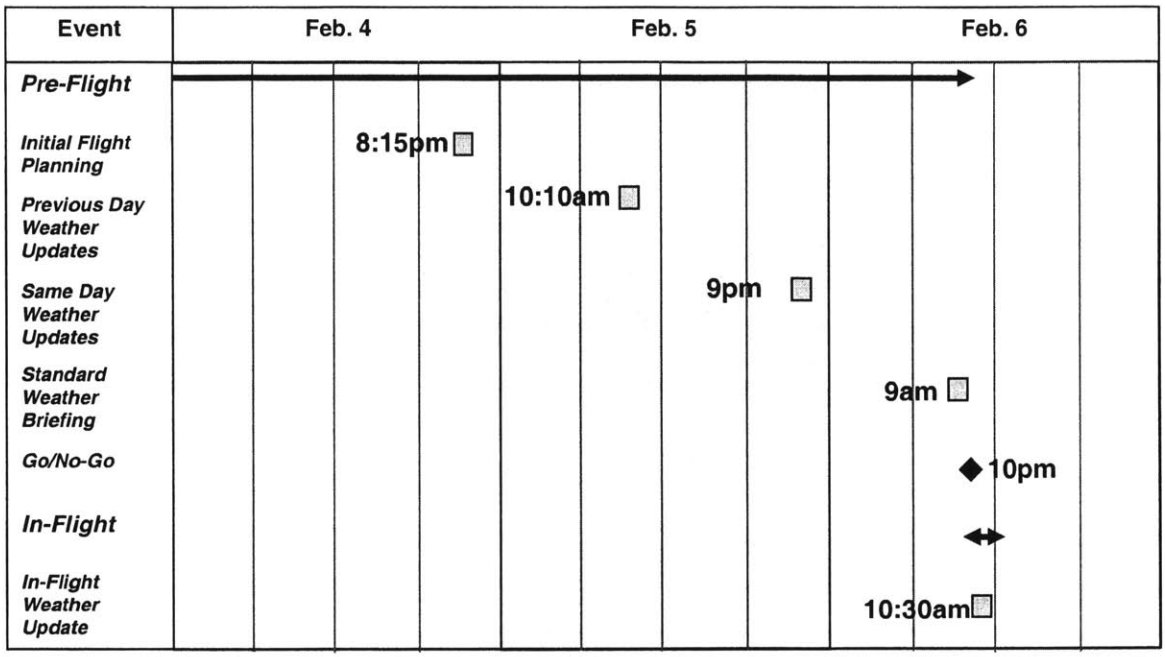


Figure 4.4.9: Gantt chart illustrating the timeline of decision points for Scenario 3

The framework of temporal decision-making introduced in Chapter Three can serve to identify at a conceptual level the various planning horizons used by the pilot in Scenario 3. Figure 4.4.10 illustrates how the various decision points can be used in the graph of the framework.

Initially (-1, 2 days), the pilot is using a stochastic representation of the threat for restricted ceilings and visibility for his flight while doing strategic planning. It is interesting to note that the information available to the pilot is actually deterministic (e.g., the Weather Prognostic Chart). However, the information is provided over a large time horizon, subsequent forecasts are contradictory, and the level of detail needed for the pilot to assert whether he will be able to operate under VFR or not is available, therefore the pilot uses a stochastic representation.

During the pre-flight briefing (e.g., at -1 hour), the pilot develops a deterministic representation that VFR conditions are observed at airports along his route of flight based on ground-based ceiling and visibility. In this scenario, it did not occur to the pilot that the visibility at his planned cruising altitude may not be as good as on the ground and that therefore the conditions may not be favourable to his VFR flight.

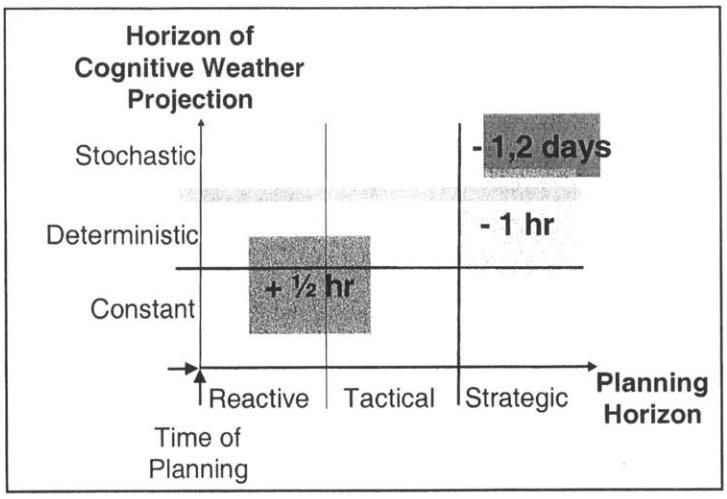


Figure 4.4.10: Framework of temporal decision-making applied to Scenario 2

Upon transitioning into the flight (e.g., at +1/2 hour), the pilot uses a constant weather mental model about the conditions in the vicinity of his location, but due to the low visibility, his foresight does not extend very far ahead. Upon encountering a cloud, the pilot decides to re-plan and return to his origin airport based on a constant representation that the conditions there are better than at a diversion airport that he considered.

4.4.4 Conclusions of Scenario 3

Scenario 3 provided a detailed illustration of how weather information may be used by a pilot who is not qualified for instrument flight in the context of a flight into low ceilings and visibility. It was observed that weather information was used mostly to support the pilot's nominal and contingency planning.

4.5 APPLICABILITY OF THE MODELS TO THE SCENARIO ANALYSIS

The walk-through of each of the three scenarios provided some insights into pilots' weather-related decision-making. Table 4.1 summarizes what issues the models were able to explain and serves as an outline for this section. Subsections 4.5.1 through 4.5.6 will recall how the models brought these insights to light and what the implications of the scenario-based analysis are.

Table 4.1: Summary of the use of the models in each scenario

Section		Scenario 1: Icing scenario for aircraft without ice protection	Scenario 2: Frontal convective weather scenario for jet aircraft	Scenario 3: Marginal VFR Conditions for non-instrument pilot
Section 3.1	**High-level model of pilot-aircraft-weather encounter**	Four-dimensional trajectory control as a key encounter mitigation strategy		
Section 3.2	**Model of aircraft-weather encounter situation dynamics**	Variability in "observability" of adverse weather regions across weather phenomena		
Section 3.3	**Model of current information system architecture**			
Section 3.4	**Model of pilots' cognitive processes**	Relevance of supporting contingency planning		
Section 3.4	**Temporal representation of pilots' functions**			
Section 3.5	**Break-down of weather forecast horizons**	Applicability of the framework of temporal decision-making		
Section 3.5	**Model of a pilot's cognitive weather projection**			
Section 3.5	**Framework of temporal decision-making**			
Section 3.6	**Representation of four-dimensional intersection**	Relevance of the 4-D intersection to high dynamics weather phenomena Pilots' perception of weather forecast accuracy		

4.5.1 Four-Dimensional Trajectory Control as Encounter Mitigation Strategy

Over the course of each scenario, it was found that weather information was useful to identify and assess available flight routes relative to adverse weather regions. When adverse weather regions could be identified with reasonable certainty, pilots planned four-dimensional flight routes that remain outside of adverse weather regions, such as upon filing a flight plan in Scenario 2.

Moreover, it was found that when the boundaries of adverse weather regions were not known with certainty due to the forecast uncertainty, such as in the early planning phase of Scenario 2, pilots may delay the definition of their flight routes until more information is available. When the boundaries of adverse weather regions are not known with certainty due to poor observability of the conditions, such as in Scenario 1 when PIREPs are not available, it was found that pilots may do contingency route planning and plan to revert to their contingency plan upon learning that their nominal route plan is no longer desirable. When the boundaries of adverse weather regions are not known with certainty due to limitations in the temporal and spatial resolution of weather information about the relatively complicated spatial and/or temporal structure of adverse weather regions, such as in Scenario 2 and 3, pilots may do contingency route planning and plan to revert to alternate route plans upon developing a constant or deterministic representation of the adverse weather field relative to their trajectory.

4.5.2 Variability in Weather "Observability" across Weather Phenomena

The ability of pilots to assess the location of the boundaries of adverse weather regions in near real-time was found to vary significantly across weather phenomena. In Scenario 2, the pilot was able to discern the boundaries of adverse convective weather regions using NEXRAD images, airborne weather radar in the proximity of storms and out-the-window observations when outside of clouds.

In contrast, in Scenario 1, the pilot was only able to discern the presence or absence of adverse icing conditions when recent PIREPs were available and by flying herself through the conditions; in addition, she may have relied on reports of freezing rain to identify positive adverse icing regions had these been available. However, the pilot's mental representation of the location of positive adverse icing regions was not deterministic due to the lack of observability of the conditions. In distinction however, the observability of a subset of ice-free regions can be much better when such information is available, and a deterministic representation of ice-free regions may be built based on the information available. A more detailed discussion of this topic is provided in the next chapter.

Prior to the flight in Scenario 3, the pilot built a stochastic representation of the likelihood that adverse weather affected his nominal route of flight, based on the cloud coverage ratio information provided as part of the METARs. For example, the forecast for the departure airport reports scattered clouds, which is defined as meaning that three to four eights (or octats) of the sky is obscured by clouds. In addition, the pilot was able to develop a deterministic representation of the location of adverse weather regions with an out-the-window view.

4.5.3 Relevance of Supporting Contingency Planning

In the pre-flight phase of each scenario, it was found that weather information was used to support pilots' planning tasks. When pilots were not able to assess with high certainty if adverse weather regions would affect their nominal flight route, due for example to a lack or excessive uncertainty of such information, they sought to assess the availability of contingency flight routes. In some cases, it was observed that information that supported contingency planning was already available while high-confidence information that supported nominal planning was not available. In other cases, specific examples of information related to icing, convective weather and low ceilings and visibilities that may be further developed to support contingency planning were identified.

While it is desirable to keep improving the accuracy of weather information and forecast to support accurate deterministic forecast that support pilots' nominal planning, it is observed that a "low hanging fruit" lies with developing and disseminating information that supports pilots' deterministic representations with regard to contingency planning.

In relation to convective weather, the implications are that if the technology for providing accurate forecast about the locations of adverse convective weather is not sufficiently mature, such as with forecasts horizons beyond 2 hours, then efforts should be pursued to provide information about the availability of contingency plans. Examples of the latter include information about the maximum altitudes of storms and the "porosity" of adverse convective weather regions, such as gaps in storm lines and areas between of airmass storms.

In the icing case, if the technology is not sufficiently mature to support the accurate assessment of the location of adverse icing areas, then efforts should be pursued to provide high-confidence information about the availability of contingency plans. Examples of the latter include information about the cloud tops and boundaries, including layers clear of clouds and regions where temperatures are above freezing, as well as the availability of airports without icing conditions. Icing remote sensing has significant potential for providing high-confidence information about icing and negative icing regions. The value of providing information about negative icing conditions should be considered in the design of such technology.

4.5.4 Applicability of Framework of Temporal Decision-Making

Each scenario provided examples of the types of information used by pilots and the cognition that can be described by the temporal representation used by pilots. The distinction between pilots' constant, deterministic and stochastic weather representations provided a structure to expose the similarities and differences of weather information and decision-making across weather phenomena.

Moreover, the framework of temporal decision-making provided a structure to explain, in the context of realistic scenarios, what horizons are relevant to pilots' weather-related decision-making and how pilots' decision-making evolves through the course of a flight. It was used to articulate the role of nominal as well as contingency plans and identify how various types of information supported these in the framework space.

Unlike other scenarios, it was found that, in the icing scenario, Scenario 1, the only transition to a deterministic representation of the nominal plan would occur based on PIREPs or icing encounter information. However, a deterministic representation with regard to the contingency routes would be supported by weather information. In the convective weather scenario, Scenario 2, it was observed that visual observations and airborne weather radar provided ideal information to progress towards shorter term representations and planning. Opportunities to improve convective weather information were nevertheless identified in relation to supporting contingency planning earlier on with cloud top probabilistic information that supports the identification of routes through convective weather areas, as well as improving the range for a deterministic representation of the convective weather areas through weather datalink. Finally, in Scenario 3, it was observed that the pilot would transition from a stochastic to a constant representation and that information to support contingency planning would again prove useful to handle the flight safely.

4.5.5 Relevance of Four-Dimensional Intersection Predictions to the Scenarios

In the three scenarios studied, the weather conditions were changing over time, and, if the adverse weather regions could be determined with reasonable certainty, the cognitive exercise of pilots could be simplified as a deterministic four-dimensional intersection assessment. In two out of three cases (Scenarios 1 and 3) however, the weather information did not support a deterministic representation of the boundaries of adverse weather regions, due to the lack of observability of the conditions in the icing case, and due to the challenges in communicating the details of the fine structure of the cloud distributions in Scenario 3. In all scenarios however, it was found that it was possible to support a deterministic representation for a subset of the regions free of adverse weather. The four-dimensional intersection prediction concept is found to be applicable to the intersection between aircraft trajectories and potential adverse regions, and conversely to the intersection between aircraft trajectories and positive clear weather regions.

4.5.6 Pilot's Perception of Weather Forecast Accuracy

It was observed that a pilot's perspective is trajectory centric. In each scenario, the pilot was trying to assess how the weather conditions would impact his or her route of flight. More specifically, the pilot's tasks involve assessing the possible intersections, in four-dimensions, between his or her aircraft trajectory and the time-varying adverse weather regions. In the case of Scenario 2 for example, the temporal resolution of the forecast did matter, and so did the spatial resolution. Even though the temporal

resolution of the Convective SIGMET used in Scenario 2 may have been adequate for the trajectory considered, the spatial resolution with regard to the expected vertical structure of the convective line would also have constituted useful information, and so would have been information about any gaps in the line for users of trajectory going across the line.

5 IMPLICATIONS FOR WEATHER INFORMATION

This Chapter articulates the implications for aviation weather information that were identified based on both the conceptual descriptive models of human-controlled adverse aircraft-weather encounter problem and the scenario-based cognitive walk-through. Section 5.1 articulates recommendations for improving weather information, Section 5.2 articulates implications for research, development and operations, and Section 5.3 presents weather-specific implications.

5.1 RECOMMENDATIONS FOR IMPROVING WEATHER INFORMATION

Two main groups of recommendations were identified. The first one relates to addressing users' four-dimensional trajectory-centric perspective, and the second involves supporting users' contingency planning.

5.1.1 Addressing Users' Four-Dimensional Trajectory-Centric Perspective

The perspective of pilots can be described as being trajectory-centric. They compare the weather information to their four-dimensional aircraft trajectories in order to select safe and efficient trajectories to conduct their flights. The scenarios of Chapter Four provided illustrations of pilots' perspective in using weather information. This is an important cognitive process that helps pilots control their trajectories to avoid adverse weather conditions, as mentioned in relation to the high-level model of Chapter Three. In order to address users' four-dimensional trajectory-centric perspective, three recommendations are presented below. The recommendations relate to capturing pilots' four-dimensional trajectory information, supporting their space-time synchronization between their trajectories and the information, and choosing forecast resolution according to the dynamics of weather and aircraft-weather encounters.

First, it is recommended that weather information tools provide weather information related to the four-dimensional trajectory-centric perspective of users. In order to do that, there is a need for the developers of weather information products to identify the most effective mechanisms to incorporate information about the planned four-dimensional trajectory of users. In addition, there is a need to identify the best means to integrate and represent information about the aircraft trajectory and the weather field in a way

that enables the users to identify the impact of the weather field on their aircraft trajectory. Finally, there is a need to identify the most effective ways to provide trajectory-centric forecasts, or forecast of how the weather conditions may affect one or multiple specific aircraft trajectories. The Route Availability Planning Tool (RAPT) developed at the MIT Lincoln Laboratory is an illustration of a weather decision-support tool for ATC that is starting to do that (DeLaura and Allan, 2003). The RAPT captures the intricacies of four-dimensional intersection predictions between aircraft on standard departure routes and convective weather forecasts in the deterministic regime. A representation of the RAPT is provided in Figure 5.1. As can be seen in Figure 5.1, RAPT shows aircraft standard departure routes out of Newark airport that are depicted in the map part of the display. In the bottom part of the display, predictions of the state of these routes in terms of whether they will be clear, impacted or blocked by the convective weather are depicted for future time intervals.

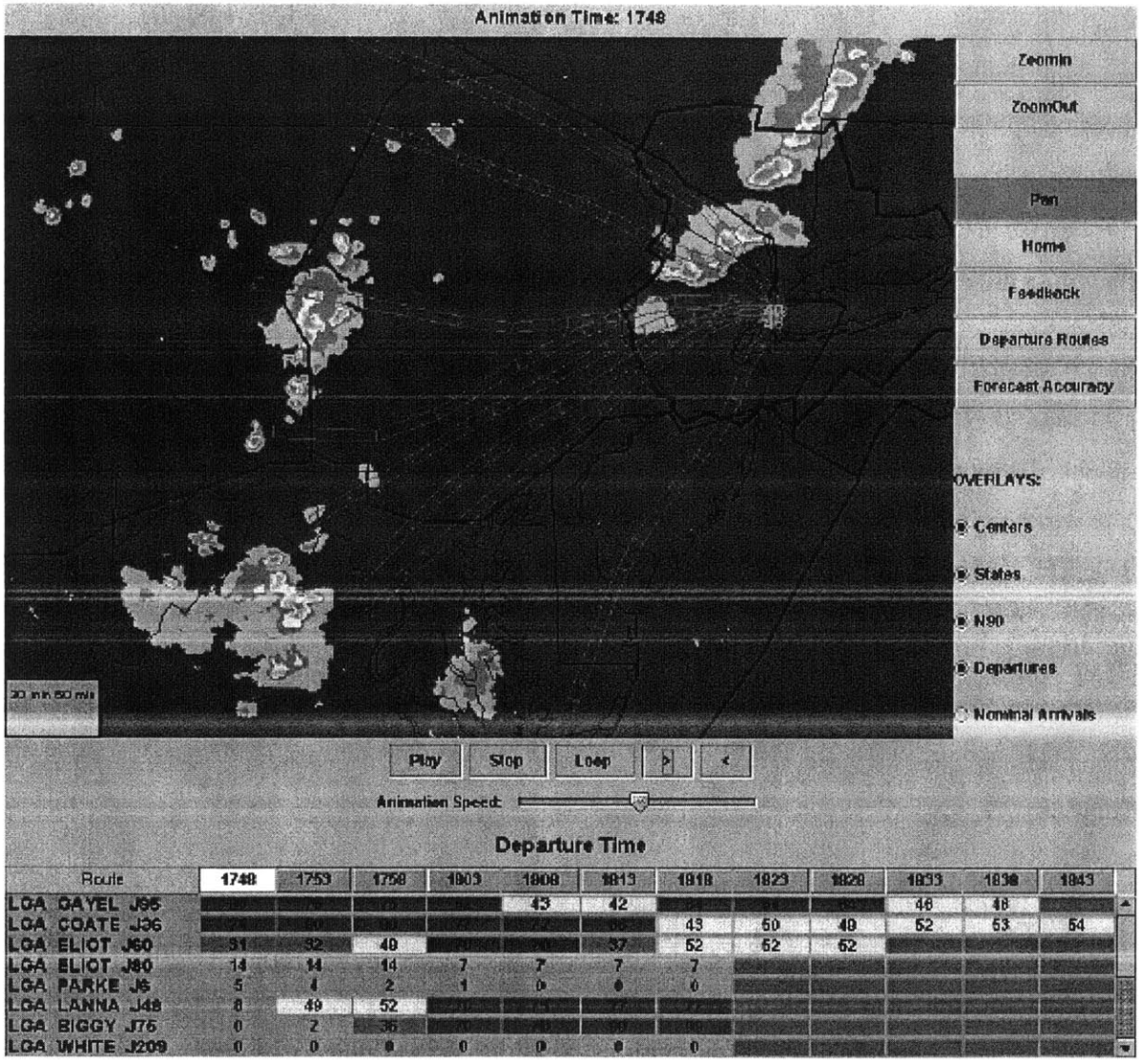


Figure 5.1: Example of Route Availability Planning Tool (Courtesy of MIT Lincoln Laboratory)

It is also recommended that weather information products be designed to ease the task of pilots in identifying the most relevant weather information as a function of their four-dimensional aircraft trajectory. This could be done for example by highlighting the weather information that is spatio-temporally synchronized with a pilots' planned trajectory. As illustrated in Scenario 2, a pilot's task involves identifying the textual weather information that is in spatial proximity to his or her planned route at times that are in phase with their planned trajectories, and he or she does that with currently available information by deciphering what pieces are most relevant.

Finally, it is recommended that the developers of weather information products consider the trajectory-centric perspective of pilots in making trade-offs relevant to the specific type of weather information. Recommendations for the development of forecasts and cockpit weather datalink products are provided in the next sections, Section 5.2 and 5.3.

5.1.2 Supporting Users in Planning for Contingencies

Contingency planning provides means for aviation weather information users to manage the uncertainty and mitigate the risk of their planned missions. Especially when using a stochastic weather mental model, contingency planning can help them articulate safe fall-back options and assess the risk of a given plan according to the availability of contingency options. Without a deterministic representation of neither the weather mental model and the availability of contingency options, some decision-makers may decide to temporarily suspend the plan or abort the mission or the flight, and therefore not operate with the best operational efficiency possible. This was illustrated mostly in Scenario 2 of the scenario-based cognitive walk-through of Chapter Four, where the pilot is dealing with an apparently stochastic adverse icing field before PIREPs become available. Other decision-makers may not rely on the information provided to them because they observe discrepancies in terms of over-warnings and false alarms by comparing the information provided and their experience with the weather.

In addition to improving risk management, contingency planning may improve the situational awareness of a pilot by tuning him or her to develop an explicit representation of what to do should the situation evolve differently from planned. This is especially important under the stochastic representation due to high uncertainty in the situation. The influence of contingency plans on a pilot's situational awareness was described as part of the model of pilots' cognitive processes presented in Chapter Three. In order to support planning for contingencies, three recommendations are presented below relation to how weather information can aid pilots identify the availability of contingency options, how it can provide *clear*

weather information that help pilots do that and how weather information can integrate users' contingency options to provide more explicit information about the weather conditions affect their options.

First, it is recommended that the developers of weather information products consider means to aid pilots in identifying the availability of contingency options. This requires that the developers of these products understand and potentially design products that are able to input and integrate the users' contingency options.

It is also recommended to further pursue the development of information about *clear weather* regions (which are regions free of adverse weather conditions). By definition, clear weather regions mark contingency routes outside adverse weather regions. In some cases, due to a different phenomenology, the observability and the predictability of clear weather regions is technically easier than the observability and the predictability of adverse weather regions. Therefore, weather information with less uncertainty, and in some cases deterministic instead of probabilistic information, may be provided to users to support contingency planning.

For example, the observability of as subset of the ice-free regions is better than the observability of icing regions. The glaciation of water into ice in the ambient airmass which directly influences the likelihood of aircraft icing is a process that depends on many variables and that is very challenging to track. This leads to the technical difficulties associated with remotely detecting and forecasting icing. There are currently no reliable means to remotely detect the ambient liquid water content and icing. Real-time information about positive icing regions can therefore be classified as *apparently stochastic* unless icing is reported in a PIREP. In contrast, ice-free regions may be identified via already routinely used remote sensing of cloud boundaries and radio-sonde observations of freezing levels. Other examples include non-convective turbulence in cases in which observable particles can be observed in the non-turbulent regions and regions clear of clouds under clear skies.

In addition, the predictability of clear weather regions is in some cases also greater than the predictability of adverse weather regions based on distinct phenomenology and characteristic lifetimes. An example is the case of icing in which the temperature field may be changing slowly but the water phase changes from liquid to solid or vice-versa may occur very quickly based on a variety of changes in the atmospheric conditions. Other examples include areas free of convective weather in stable airmasses and the spreading of dry airmasses over moist ones.

As already mentioned, some information about clear weather regions is already routinely generated by various components of the weather information system, including surveillance, modelling and forecasting, dissemination and presentation systems. Following the recognition that this information is valuable to decision-makers, there is an opportunity to improve information by improving the temporal resolution, the spatial resolution and the coverage of these weather information system elements.

The third recommendation is to make the representations of weather information more explicit about the availability of contingency options in weather information tools. An example of an icing information tool is provided in Appendix E, wherein a planar view provides information about the impact of the presence of icing conditions on the availability of cruising altitudes over a geographical area. In order to do this well, the weather information tool would need to incorporate means to capture information about users' planned trajectories as well as their available cruising altitudes.

5.2 IMPLICATIONS FOR RESEARCH, DEVELOPMENT AND TRAINING

The work presented in this thesis has implications for research and development efforts focused on weather information systems and products as well as on the training of pilots. These implications are presented in relation to forecasting, cockpit weather datalink products and training and, when relevant, recommendations on these topics are provided.

5.2.1 Implications for Forecasting

Recommendations for improving forecasts are presented in this sub-section. These include implications on the desirable selection of forecast resolution, on the forecasting of clear weather regions and implications for trajectory-centric forecasts.

It was observed in Chapter Three that, for a given temporal and/or spatial resolution, the performance of a forecast is linked to the dynamics and scale of weather conditions. Reversing this statement, we see that for the same space-time forecast performance, the dynamics and scale of the weather conditions influences the desirable spatial and temporal resolutions of forecasts. It is therefore recommended that forecast features such as their spatial and temporal resolution be selected as a function of the dynamics and the spatial extent of weather conditions. The framework of integrated space-time forecast assessment can serve to do that.

The dynamics of clear weather regions are in some cases characterized by longer phenomena lifetimes than those of adverse weather regions. Hence the predictability of clear weather regions is in some cases greater than the predictability of adverse weather regions. By forecasting clear weather regions, there appears to be an opportunity to improve some weather forecasts useful to pilots in two related ways: 1) by increasing the horizons over which deterministic forecasts may be made; 2) by reducing the uncertainty of weather information over a given forecast lead time. Hence in some cases, there is an opportunity to improve the information available to a decision-maker so as to potentially support a deterministic representation of the availability of contingency options instead of only supporting a stochastic representation that adverse weather regions may be of concern. The recommendation on developing forecasts of clear weather regions mentioned in Sub-section 5.1.2 applies here.

Pilots are more concerned with the boundaries of weather regions in the vicinity of their spatial trajectories at times that are in phase with their spatial trajectories than at locations and times that are remote from their four-dimensional aircraft trajectories. High spatial and temporal resolution of information about dynamic weather conditions at critical trajectory points (e.g., an origin or destination airport) has more value in some cases than information with high temporal resolution about adverse weather region away from these points or in an area that the pilot can altogether avoid by re-routing. It is therefore observed that the value of forecast resolution in space and in time depends on the geometry and the dynamics of adverse aircraft-weather encounters. There is an opportunity for weather forecasters to take into account the trajectory-centric perspective of pilots into consideration and to research new ways to provide trajectory-based forecasts. For example, there is an opportunity to investigate the value of increasing the grid density of numerical weather forecasts in the vicinity of major airports.

5.2.2 Implications for the Development of Cockpit Weather Datalink Products

Implications of the work presented in the previous chapters and recommendations for improving cockpit weather datalink products are presented below. They include recommendations for making bandwidth trade-offs that meets with pilots needs for information and the identification of the urgent need to find ways to address users' aircraft-weather mental model synchronization in order to prevent encounters with adverse weather.

As described above, pilots are more concerned with the boundaries of weather regions in the vicinity of their spatial trajectories at times that are in phase with their spatial trajectories than at locations and times that are remote from their four-dimensional aircraft trajectories. It was therefore observed that the value

of spatial and temporal resolution of information on adverse weather regions depends on the geometry and the dynamics of adverse aircraft-weather encounters. There is an opportunity for cockpit weather datalink product designers to take into account the trajectory-centric perspective of pilots in assessing the trade-offs in providing datalink over limited bandwidth. One way to quantify the value of the spatio-temporal resolution of the information is to assess a metric that quantifies the desired level of performance of the forecast for a given level of weather dynamics.

Cockpit weather datalink products influence pilot decision-making by serving to update and re-synchronizing the pilot's weather mental model relative to aircraft trajectories. In order to do this correctly, the weather information product should depict the time of information production. In addition, in order to prevent weather encounters due to the datalink information, it is critical to identify the best means to synchronize the weather and aircraft time-varying information such that the user is able to identify their spatio-temporal relationship and possibly their proximity. This is especially important in cases in which the depiction of adverse weather regions becomes old and the aircraft is potentially faced with an encounter.

5.2.3 Implications for Pilot Weather Training and Operations

Implications and recommendations for improving pilot training are presented in this sub-section. They include implications on the lack of understanding of the time-varying and uncertainty-related aspects of weather, weather information and predictability as well as implications on weather-related risk management and opportunities to address these issues with pilot training.

An important part of weather-related decision-making relates to the time-varying aspect of weather conditions, weather predictability and weather information. Without an adequate understanding of the dynamics of weather conditions, novice pilots sometimes employ constant representations of weather phenomena for longer than is appropriate, potentially leading to exposure to adverse weather. Without an understanding of the time-varying aspect of weather predictability and the chaotic uncertainty, novice pilots have been witnessed to believe weather forecasts with large lead times and not attempt to update their weather mental model with forecasts of shorter lead times or recent observations. Without an adequate understanding of the time-varying aspect of weather information combined with the limitations in weather predictability, pilots may not seek or know when to obtain the most recent weather observations or forecasts.

In response, it is recommended to improve the training of pilots by including as part of the weather theory a more exhaustive and structured coverage of the interdependent topics of weather dynamics, phenomena lifetimes, weather predictability, and the time-varying features of weather information. The concept of temporal regimes of weather predictability constitutes a foundation for discussing these topics. It articulates the relationship between projection horizons, uncertainty in weather conditions, and information production. It can serve as a basis for decision-makers to develop a mental representation of their cognitive projection and to critically assess weather information.

Weather information has inherent limitations for a number of reasons and this has implications for training pilots to better manage risk. First, the atmosphere is not sampled exhaustively, continuously and perfectly and some important aviation impact variables are not directly observables but must rather be inferred. Also, due to the chaotic nature of weather, weather conditions are not well predictable beyond some temporal horizons. Because of these reasons, the weather mental model that pilots develop shouldn't be perfect either and should take into consideration a representation of uncertainty. In addition, pilots should seek to gather situational awareness to continuously validate and correct their weather mental model in order to make most well-informed decisions. Finally, pilots should be trained to make decisions where they balance the uncertainty and the risks associated with their decisions. One way that can be used by pilots to manage risk is for them to develop a representation of one or more contingency plans and regularly assess their availability. Contingency planning is especially relevant in situations in which uncertainty is elevated, such as upon using a stochastic representation of the weather. In these cases, pilots can reduce the perceived and potentially the actual risk that a "go" decision would lead to a bad outcome by having in mind a course of action for adverse aircraft-weather encounters. Without doing so, some pilots may elect not to go or continue and reduce the efficiency of their operations. Others may opt to go without the most exhaustive set of information and without the ability to adapt their plans should conditions turn out to be different than anticipated.

For pilots who are properly trained to develop contingency plans, weather information can help them do that. Examples include information on the location of regions free of adverse weather and information on how these may intersect with pilots' planned or alternate four-dimensional aircraft trajectories. In some cases, due to observability and phenomenology reasons, information about clear weather regions may support a deterministic representation of the location and availability of these regions while the appropriate representation that pilots should have about adverse weather regions remains stochastic. Examples include information about the freezing level, cloud boundaries, regions away from fronts and regions where negative PIREPs have been reported. Therefore, it is recommended to include as part of the

training on weather-related decision-making the treatment of contingency planning and the description of what information can help pilots in planning for contingencies.

5.3 IMPLICATIONS FOR INFORMATION ON SPECIFIC TYPES OF WEATHER CONDITIONS

Implications that are specific to the development of icing and convective weather information systems are presented in this Section.

5.3.1 Implications for Icing Information

Implications for improving icing information are presented in this section. They touch on icing remote sensing and ice-free region information.

Providing information with little uncertainty and inaccuracy to pilots is desirable in order to support more informed decisions. In the case of icing, means to support pilots' deterministic representation about icing conditions can be accomplished in three ways: 1) by providing information about icing PIREPs; 2) by providing information about the location of freezing precipitations; 3) if the technology can be developed and operated reliably, by providing icing remote sensing information. PIREPs have inherent limitations related to their scarcity, subjectivity and the dependency on aircraft type and many times icing is present outside of freezing precipitations. Icing remote sensing deployed in a network would increase tremendously the spatial and temporal coverage of icing conditions and provide means to validate and improve icing nowcasts and forecasts.

In addition to developing technology to detect adverse icing regions, it is recommended to pursue the development, deployment and operation of technology that could support complementary information about ice-free regions. Three main reasons serve to justify this recommendation: 1) the greater observability of some ice-free regions over the observability of icing regions; 2) the greater predictability of the evolution of some ice-free regions over icing regions due to the respective phenomenologies; 3) the influence of ice-free region information on pilots' risk mitigation strategies. These reasons are explained below.

As explained in Sub-section 5.1.2, the surveillance of some ice-free regions is technologically easier than the positive identification of icing regions. The surveillance of icing conditions involves the identification of the state of three parameters, including droplet size distribution (DSD), liquid water content (LWC) and temperature. There are currently no good remote sensing systems that can detect the droplet size distribution. Therefore, the identification of high-confidence icing regions is not currently achievable. In distinction, a subset of ice-free regions may be identified deterministically, including: 1) regions where the temperature is above the freezing level and 2) regions where the liquid water content is low, such as outside of clouds and precipitations. In addition, the remote sensing of a subset of these ice-free fields is routinely conducted under the current aviation weather information system. Examples include the satellite detection of cloud tops, the ground-based detection of cloud bases, and the radio-sonde measurement and modeling of temperatures aloft.

Second, the variations over time of the spatial distribution of physical properties characterizing a subset of ice-free regions are in some cases slower and more predictable than the ones of positive icing regions. Examples include the temporal variations of the temperature field compared to the temporal variations of the liquid water content due to water phase changes.

Finally, ice-free region information has some value in pilots' risk mitigation strategies. Because there is not extensive information that supports pilots in developing a deterministic representation of the adverse icing field, then pilots are left with decisions under high uncertainty and in which they use a stochastic representation of the icing threat. In this context, the identification of the availability of safe fall-back options such as ice-free regions provides a mechanism for them to deal with the uncertainty and to manage the risk with a strategy that includes tactical deviations in the case of encounters or near-encounters.

5.3.2 Implications for Convective Weather Information

In distinction to icing, there exists a good surrogate for providing nowcasts of adverse convective weather regions. Convective weather forecasts with several hours of forecast horizons are nevertheless stochastic, and pilots using this information should use a stochastic representation.

There are several implications of that for how convective weather information and decision-making can be positively influenced. First, because there is good observability of adverse convective weather, then the opportunity for decision-makers to update their weather mental model about the conditions should be

coupled with an operational opportunity to update their plan instead of being rigidly tied to their strategic plan. Also, under the stochastic regime of adverse convective weather predictability, there are ways to improve the information relevant to the decision-makers by providing them information that supports contingency planning. Even when convective weather forecasts can not provide a good estimate of the expected location of fronts or the boundaries of storms, information about a subset of weather regions clear of convective weather that can be known with little uncertainty can help pilots make more informed decisions than without this information. Useful elements of information includes an upper bound on echo tops, a lower bound on the expected size of gaps in front lines, an outer bound on the expected extent of front lines and an upper bound on the expected maximum widths of front lines. In addition, updating information so as to support a deterministic representation of the boundaries of these regions free of convective weather may also support pilots in dealing with the uncertainty associated with the ability to fly through and complete their missions.

5.4 SUMMARY

General recommendations for improving weather information that have implications for various weather information research and development efforts were presented. The implications that most directly affect the development of information system elements such as forecasting and cockpit weather datalink were presented. In addition, the implications that most directly affect weather-specific development efforts in relation to convective weather and icing were provided.

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6 CONCLUSIONS

In order to separate aircraft from adverse weather and maintain safety and efficiency in the air transportation system, weather information is used to support awareness of the key decision-makers. New technologies for the surveillance, modeling, dissemination and presentation of weather information are being developed to enhance the capabilities of air transport operations to operate in all weather conditions. However, there are currently no general methods to help evaluate fundamental weather information issues and more effective ways to assess the efficacy of the weather information are desirable. These issues were discussed in Chapters One and Two.

A human-centered systems approach was used to study the problem of human-controlled adverse aircraft-weather encounter. Building on results from prior work involving interviews and experiments with pilots, a series of conceptual models relating to the three main aspects of the problem were developed and described in Chapter Three. They included models of situation dynamics, pilot and information system. The model of pilots' cognitive processes provides a structure that can serve to discuss pilot decision-making. In order to study the role of time in weather-related decision-making, a framework of temporal decision-making was developed. The framework builds on a new representation describing the temporal regimes of pilots' cognitive weather projection that could serve as a basis to train pilots about the role of time and uncertainty in weather-related decision-making. The framework is used to illustrate the planning and projection horizons relevant to pilots' decision-making at various phases of a flight and when dealing with various weather phenomena. Also, in order to address the discrepancies that were observed between traditional methods for assessing the performance of some weather forecast and the perspective of pilots in assessing them, a framework of integrated space-time forecast evaluation was developed. Results from the framework can be used to identify the value of forecast valid times as a function of the dynamics of adverse weather regions. The models were validated using focused interviews with ten national subject matter experts in aviation meteorology or flight operations. The experts unanimously supported the general structure of the models and made suggestions on clarifications and refinement which were integrated in the final models.

Providing a complementary and independent process to study the adverse aircraft-weather encounter problem, a scenario-based cognitive walk-through was conducted. Chapter Four describes the cognitive walk-throughs of three key examples of adverse weather conditions, including icing, convective weather

and restricted ceilings and visibilities. The scenarios were built using actual meteorological information and the missions and pilot decisions were synthesized to investigate important weather encounter events. The walk-through provided a detailed illustration of the cognitive information processing and decision-making of pilots during a sequence of relevant time events. The framework of temporal decision-making was used to structure the discussion on pilots' temporal representation which provided insights into the limitations of weather information products. It was found that the models of Chapter Three provided insights into the analysis of the cognitive walk-throughs.

The cognitive walk-throughs of Chapter Four and the models of Chapter Three were used to identify opportunities for improving weather information and training. General recommendations for improving weather information related to two main topics: 1) addressing certain users' trajectory-centric perspective with weather information; 2) enabling certain users to plan for contingencies in the case of uncertain information about adverse weather regions. In addition, implications for development efforts related to specific weather information system elements such as forecasting and cockpit weather datalink were presented, and implications for pilot training were also described. Finally, weather-specific implications for icing and convective weather information were provided.

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APPENDIX CONTENTS

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APPENDIX A – ACCIDENT ANALYSIS DATA

Appendix Table A: Average aviation accident statistics for 1987-1996 (NTSB, 2000 and 2002)

	Accidents		Fatal Accidents					
	Annual Average Number	**% Weather Related**	**Annual Average number**	**% weather related**	**Fatalities**	**Million hours flown**	**Accidents per million hours**	**Fatalities per million hours**
Part 121	28.0	26.8	4.6	17.0	171.7	12.2	2.3 (0.6)	14.0
Part 135								
Scheduled	18.0	29.3	4.5	40.0	30.9	2.4	7.8 (2.3)	12.8
Nonscheduled	89.8	31.1	26.2	42.2	62.4	2.2	41.3 (12.8)	28.3
General Aviation	2157.0	23.0	423.3	30.0	764.3	25.8	83.7 (19.3)	29.6
Aggregate	2292.8	23.4	458.6	30.7	1029.3	42.6	53.8 (12.6)	24.2

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APPENDIX B – BACKGROUND ON ADVERSE WEATHER PHENOMENA

Adverse weather affects flight operations differently according to several factors, including the phenomenology and intensity of weather phenomena, the aircraft type and characteristics, the nature of flight operation and pilot experience. In order to provide to the non-expert reader a basic understanding of the relevance of this thesis in providing mitigation strategies, this appendix reviews for four types of weather phenomena the following questions:

1) Nature of concern
2) Types of conditions
3) Hazard mitigation strategy
4) Spatial extent
5) Variation over time
6) Hazard index

Four weather phenomena are included in the discussion of Appendix B, including icing, convective weather, non-convective turbulence and restricted ceilings and visibility. They were selected based on their significant impact of aviation safety and efficiency, and their common aviation impact characteristics and desirable operational mitigation strategies.

B.1 Icing

Nature of Concern

Aircraft flight through icing conditions leads to the accretion of ice layers on exposed surfaces. Ice accretion on wings, vertical and horizontal stabilizers and propeller blades may dramatically affect the performance, stability and control of aircraft, by reducing lift, increasing drag and weight, reducing thrust, and leading in the worse cases to aircraft stalls, loss of control, and ultimately incidents and accidents. In jet aircraft, chunks of ice breaking loose from the aircraft surfaces can be ingested into the engine, causing damage to compressor blades.

Ice accretion on navigation instrument and radio antennae may induce instrument errors or degrade drastically the navigation and communication capabilities of aircraft due to shielding or even breakage.

Accretion of ice on windshield may degrade the out-the-window visibility and the ability of pilots to control aircraft. Finally, icing on brakes and landing gear may reduce the ability to land safely.

For icing to occur, the aircraft must be cold (temperature below 0°C) and the area it flies through must contain supercooled water drops or droplets. The severity of ice accretion on aircraft depends on the length of exposure to the conditions and the rate at which ice may accrete, which in turn depends on atmospheric conditions as well as aircraft characteristics (e.g., surface shapes, operating speed, ice protection equipment). The implications of ice accretion in terms of the severity will in turn depend on aircraft performance characteristics such as stall speed, excess engine thrust, and ice protection equipment.

The U.S. National Transportation Safety Board's (NTSB) "most wanted" list of safety improvements has been including since 1997 the recommendation to the Federal Aviation Administration to "[revise] the requirements for testing and certifying aircraft ice protection systems, especially for those on turboprop aircraft. The NTSB [has] also [urged] the FAA to research and develop a new generation of anti-icing and de-icing systems." (U.S. NTSB, 2002).

Types of conditions

Icing conditions have been classified as clear, rime or mixed ice according to the characteristics of the ice accreted on aircraft surfaces after aircraft encounter with freezing precipitation, supercooled fog or supercooled cloud droplets. The type of icing typically depends on the temperature and the number and size of droplets within a cloud.

Clear ice is typically associated with drops that are large as in rain and cumuliform clouds. Upon impact with aircraft surfaces, these droplets spread over the structure, freezing slowly but densely and adhering strongly to the aircraft surface. In distinction, rime ice forms when droplets are small, such as those in stratified clouds or light drizzle. These droplets freeze immediately when they strike aircraft surfaces, trap air and form brittle ice. It is generally lighter and easier to shed. Mixed ice forms when drops vary in size or when liquid drops are intermingled with snow or ice particles (U.S. D.o.T., 1975; Lester, 1997).

Hazard mitigation strategy

There are essentially two methods by which the impact of adverse icing conditions on flight operations may be mitigated. The first one involves improving the tolerance of aircraft to adverse icing conditions, and the second involves separating aircraft from adverse icing conditions. The intensity of conditions

adverse to aircraft operations is highly dependent of specific aircraft characteristics, but there are icing conditions that are adverse to all aircraft operations. Therefore, the characteristics and level of ice protection of aircraft only shifts the boundaries and types of icing conditions that are hazardous to aircraft operations.

The Federal Aviation Regulations (FARs) define the types of conditions that aircraft should avoid as a function of the equipment and the type of flight operations. The types of conditions are defined as a function of the severity of aircraft encounters, according to a four-point scale, including trace, light, moderate and severe icing. The severity of aircraft icing is defined in the Airmen Information Manual (2003) according to the influence of the rate of ice accumulation on the level of hazard to the flight operation.

Spatial extent

The climatology of icing conditions has not extensively been studied due to the lack of observability of the icing conditions based on instrumentation and remote sensing systems. Although it is not well know how large icing areas may be, it is noted that they could theoretically extend spatially as much as cloud systems do. Therefore, they can be as small as a few dozens of feet to as large as several hundreds of kilometers wide horizontally, and be as tall as a few dozens of feet high in a single or in multiple layers and be as tall as over 50,000 feet of altitude..

Variation over time

Since icing conditions develop based on the concordance of three factors, including the temperature, droplet size distribution (DSD) and liquid water content (LWC), the temporal evolution of adverse icing regions may be linked to the temporal variations in these three weather phenomena. Adverse icing regions may therefore grow in space at a rate as fast as the region where temperatures are falling below the freezing level in regions where DSD and LWC are favorable to icing conditions, and may persist for long periods of time if the atmosphere is very stable and the three key variables do not change over time.

Hazard index

The level of hazard of icing is rated in the operational context according to the severity of encounters of aircraft with icing. Appendix Table B provides an overview of the severity levels used. As can be noted in the table, it is based on a subjective and aircraft specific basis as a function of the influence of the rate of ice accumulation on the level of hazard to the flight operations. A four point scale is used to rate the hazard level and includes trace, light, moderate and severe icing (Airmen Information Manual, 2003).

Various government organizations including NCAR, the FAA and ICAO are working on ways to improve on the current hazard index by shifting towards objective and aircraft-independent metrics.

Appendix Table B: Icing severity levels defined in AIM

Trace	Ice becomes perceptible. Rate of accumulation slightly grater than sublimation. Deicing/anti-icing equipment is not utilized unless encountered for an extended period of time (over 1 hour)
Light	The rate of accumulation may create a problem if flight is prolonged in this environment (over 1 hour). Occasional use of deicing/anti-icing equipment removes/prevents accumulation. It does not present a problem if the deicing/anti-icing equipment is used.
Moderate	The rate of accumulation is such that event short encounters become potentially hazardous and use of deicing/anti-icing equipment or flight diversion is necessary
Severe	The rate of accumulation is such that deicing/anti-icing equipment fails to reduce or control the hazard. Immediate flight diversion is necessary.

B.2 Convective Weather

Nature of concern

Convective weather including thunderstorms, is dangerous to flight operations due to the severity and the diversity of the weather phenomena that may be associated with it. The list of adverse phenomena that may be present inside or in the vicinity of a thunderstorm cell includes turbulence, icing, hail, lightning, tornadoes, gusty surface winds, low-level wind shear, adverse effects on the altimeter, and restricted ceilings and visibilities. The effect of turbulence, icing and restricted ceilings and visibilities are explained in the three next subsections in details. To touch on the effect of other phenomena, hail has been observed to seriously affect the skin of aircraft, affecting airflow and causing an expensive need for aircraft repair, as well as the structural integrity of engine blades. Lightning can lead to electric surges and cause instrument failures. Tornadoes could lead to accidents due to aircraft loss of control. Low level wind shear has caused several accidents in the past by leading aircraft to fly in the ground due to significant loss of performance.

Types of conditions

Thunderstorms are usually classified as either air mass thunderstorms versus line (or steady state) thunderstorms. The intensity, spatial extent and duration will vary greatly according to this classification. Air mass thunderstorms most often result from surface heating, and reach maximum intensity and

frequency over land during middle and late afternoon. Steady state thunderstorms, in contrast, are usually associated with weather systems, including fronts, converging winds, and throughs aloft that will form in squall lines.

Hazard mitigation strategy

The Airmen Information Manual recommends pilots to avoid severe thunderstorms and thunderstorms giving an intense radar echo by at least 20 miles laterally, and to clear the top of a known or suspected severe thunderstorm by at least 1,000 feet altitude for each 10 knots of wind speed at the cloud top (FAA, 2003, 1-1-26).

Spatial extent

Depending on the season and the climate, individual thunderstorms may have diameters ranging between 5 miles and 30 miles. Cloud bases range from a few hundred feet in very moist climates to 10,000 feet or higher in drier regions. Tops generally range between 25,000 and 45,000 feet but occasionally extend above 65,000 feet (FAA, 1975). Lines of thunderstorms can be as long as a thousand miles and be as wide as a hundred miles (check and ref).

Variation over time

A single thunderstorm will progress through a life cycle that involves cumulus growth that could exceed 3,000 feet per minute vertically. Air mass thunderstorms can last between one hour and a few hours, while line thunderstorms may last for several hours (FAA, 1975). Drift velocities of thunderstorm cells could be anywhere between 0 and several dozens of miles per hour. Depending on the location, the frequency of occurrence of thunderstorms in the continental U.S. lies between a few and 90 storms per year, and the average number of days with thunderstorms over the summer can reach up to 50 days.

Hazard index

Weather radars monitor atmospheric phenomena primarily by detecting the backscattered energy from raindrops. The U.S. National Weather Service has specified six reflectivity slabs, with corresponding video integrator and processor (VIP) levels that correspond to rainfall of different intensity levels specified in Appendix Table C (Mahapatra, 1999 and FAA, 1985).

Appendix Table C: NWS standard reflectivity levels for different rainfall intensities

VIP Level		NWS Reflectivity (dBZ)	Rainfall Category	Rainfall rate (in/hr) Convective
1	18-30	18-30	Light (mist)	Less than 0.2
2	30-38	30-41	Moderate	0.2-1.1
3	38-44	41-46	Heavy	1.1-2.2
4	44-50	46-50	Very Heavy	2.2-4.5
5	50-57	50-57	Intense	4.5-7.1
6	>57	>57	Extreme (with hail)	More than 7.1

An aviation rule-of-thumb is used by pilots and controllers to avoid VIP level 3 and above (American Airlines, 2002, Crowe and Miller, 1999), which are defined to pilots according to Appendix Table D. These may be used in weather reports or referred to by air traffic control (ATC) to indicate convective precipitation intensity.

Appendix Table D: VIP levels known to pilots via airborne weather radar

VIP Level	On Board Radar Color	Convective Precip Intensity
1	Green	Weak
2	Yellow	Moderate
3	Red	Strong
4	Red	Very Strong
5	Red	Intense
6	Red	Extreme

B.3 Non-Convective Turbulence

Nature of concern

The Glossary of Meteorology (2000) defines aircraft turbulence as "irregular motion of an aircraft in flight, especially characterized by rapid up-and-down motion, caused by a rapid variation of atmospheric wind velocities. This can occur in cloudy areas (particularly inside or in the vicinity of thunderstorms) and in clear air".

At lower intensities, the rapid and erratic accelerations induced by turbulence may cause dislocation of objects and passengers within the aircraft cabin, resulting in serious passenger injuries. Stronger random oscillations forced on the aircraft and its structural members may result in high stresses, metal fatigue, and even lead to rupture and structural failure of aircraft in flight. Finally, turbulence may excite strong rigid dynamic modes which can lead to difficulties in controlling aircraft, or even loss or control and consequent accidents (Mahapatra, 1999)

Hazard mitigation strategy

Pilots may avoid altogether areas of turbulence when it is known to them, based on weather forecasts as well as based on pilot weather reports of turbulence. If penetration is inevitable due to lack of sufficient warning in order to request a different altitude, pilots reduce aircraft speed to a turbulence penetration speed/Mach number that will reduce the stress on the aircraft and potentially the discomfort in the cabin. In addition, pilots of passenger aircraft will also share the information with and influence the operations in the cabin, leading to either passengers to be requested to be seated, food carts to be put away and possibly that all flight attendants to be seated.

Spatial extent

Non-convective turbulence regions may be characterized spatially by one or more layers thick of a few thousands of feet and extending over hundreds of miles.

Variation over time

Non-convective weather regions may develop over the period of a few minutes and persist for minutes to hours, depending on the relative location of the jet stream and the dynamics of gravity waves. Little climatology information is available.

Hazard index

Similarly to icing conditions, the level of hazard of turbulence is rated in the operational context according to the severity of encounters of aircraft with turbulence conditions. Appendix Table E provides an overview of the severity levels used, including light, moderate, severe or extreme turbulence.

Appendix Table E: Turbulence report criteria

Light	Causes slight, erratic changes in altitude and/or attitude, and rhythmic bumpiness as occupants feel a slight strain against seat belts.
Moderate	Similar to light, but of greater intensity, with rapid bumps or jolts, and occupants feel a slight strain against seat belts.
Severe	Turbulence that causes large, abrupt changes in altitude and attitude, and large variations in airspeed, with the aircraft temporarily out of control. Occupants are forced violently against their seat belts and objects are tossed around, with food service and walking impossible.

Extreme	The aircraft is tossed about so violently that it is practically impossible to control, and structural damage may occur.

In distinction to turbulence, rhythmic bumpiness may be reported as chop instead of turbulence. In addition, the temporal effect of turbulence on the aircraft is also typically reported, as defined according to a three point scale presented in

Appendix Table F: Turbulence frequency reporting

Occasional	Less than 1/3 of the time
Intermittent	1/3 to 2/3 of the time
Continuous	More than 2/3 of the time

Various government organizations including NCAR, the FAA and ICAO are working on ways to improve on the current hazard index by shifting towards objective and aircraft-independent metrics.

B.4 Restricted Ceilings and Visibilities

Nature of concern

For pilots who are not qualified for flight into instrument meteorological conditions (IMC), exposure to the conditions may lead them to lose control of their aircraft due to spatial disorientation and collide with the terrain.

Types of conditions

Visibility is defined as the greatest distance at which selected objects can be seen by the unaided eye. The height above the surface of the Earth at which the lowest layer of clouds or obscuring phenomenon is reported as broken, overcast or totally obscured defines ceiling (U.S. Dep. Of Commerce, 1988).

Ceilings and visibilities are measured at airports and modelled and predicted over terminal and regional areas in forecasts, according to the types of conditions mentioned in Appendix Table G.

Appendix Table G: Types of conditions according to ceiling and visibility

Type of Conditions	Acronym	Ceilings (feet)	Visibility (statute miles)
Visual Flight Rules	VFR	Ceiling > 3000	Visibility > 5
Marginal Visual Flight Rules	MVFR	3,000 ≥ Ceiling > 1000	5 ≥ Visibility > 3
Instrument Flight Rules	IFR	1,000 ≥ Ceiling > 500	3 ≥ Visibility > 1
Low Instrument Flight Rules	LIFR	Ceiling ≤ 500	Visibility ≤ 1

Hazard mitigation strategy

Pilots trained for instrument flight who operate aircraft that are equipped and certified for flight into IMC may operate safely in conditions of restricted ceilings and visibilities. Pilots who are not adequately trained should avoid conditions of restricted ceilings and visibilities.

Spatial extent

Cloud structures can be as small as a few dozens of feet to as large as several hundreds of kilometers wide horizontally, and be as tall as a few dozens of feet high in a single or in multiple layers and be as tall as over 50,000 feet of altitude.

Variation over time

Clouds and low visibility areas as a function of the relative humidity and the availability of condensation nuclei. The temporal variation of relative humidity in a spatial field varies according to temperature variations as well as lifting. Clouds of horizontal development such as stratus, altostratus, and fog banks can develop in the order of minutes and spread over large areas when the temperature reaches the condensation point and dissipate very quickly as well upon surface heating. Clouds associated with vertical development such as cumulus and cumulonimbus clouds may develop in the order of minutes as well according to surface heating and the availability of a lifting agent.

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APPENDIX C –SURVEY OF INFORMATION NEEDS FOR OPERATING IN ICING CONDITIONS

Vigeant-Langlois, L. & R.J. Hansman, 1999: Pilot information needs and strategies for operating in icing conditions. Proceedings of the 10th International Symposium on Aviation Psychology, Columbus, OH.

PILOT INFORMATION NEEDS AND STRATEGIES FOR OPERATIONS IN ICING CONDITIONS

Tenth International Symposium on Aviation Psychology
May 3rd to 6th, 1999, Columbus, OH

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ABSTRACT

Pilot current use of icing information, pilot encounters and strategies for dealing with in-flight aircraft structural icing situations, and desired attributes of new icing information systems were investigated through a survey of pilots of several operational categories. The survey identified important information elements and frequently used information paths for obtaining icing-related information. Free-response questions solicited descriptions of significant icing encounters, and probed key icing-related decision and information criteria. Results indicated the information needs for the horizontal and vertical location of icing conditions and the identification of icing-free zones.

INTRODUCTION

Aircraft icing remains a significant aviation weather hazard for both civil and military aircraft operations. Under the commission of the National Aeronautics and Space Administration (NASA) Aviation Safety Program, a joint effort is under way for developing remote sensing capability via both airborne and ground-based technologies, for detecting weather conditions conducive to aircraft structural icing (Huettner, 1996).

In order to assure that the icing information products under development meet the needs of the operational community, an integrated human centered system approach (Hansman *et al.*, 1997), which considers the human operator as one element of a larger complex flight critical system, was applied in the definition of information requirements of in-flight icing avionics systems. As a first step of this approach, a survey to study pilots information needs and strategies for operations in icing conditions was conducted. This paper will document the results of this study.

METHOD

The survey was organized to explore three aspects of the impact of information on pilot icing-related decision making:

- Pilot use of currently available information
- Pilot decision-making approach to dealing with potential and actual icing situations
- Identification of desired attributes of new icing information systems

Survey Design

The survey was divided in seven sections which are described below.

Section 1 - Subject Background Information: The subject pilots were asked to indicate their primary and secondary categories of operation, from the following list: General Aviation (GA), Corporate, Commuter Airline, Major Air Carrier, Civil Helicopter, Military Helicopter, Military High-Performance and Military Transport. Pilots were also asked to indicate their certificates and ratings held, flight experience, geographic region of operation and other factors pertaining to their flight operations.

Section 2 - Importance of Currently Available Information: Pilots were asked to rate the importance of various currently available information elements for making icing-related decisions. Elements were listed in three categories: *Direct Visual Observations, Instruments and Sensors*, including information elements directly observable, such as clouds and visibility, and information obtained by the pilot from onboard instruments such as temperature probes and weather radar, etc.; *Reported Observations and Measurements,* including information collected at other locations by different users and reported to the pilot, such as airport surface observations (*METAR*s), pilot reports (*PIREP*s), "party-line" information (PLI), etc.; *Forecasts*, including all relevant weather forecasts such as icing SIGMETs, winds aloft forecasts, etc.

Table 1 depicts the importance rating scale. Pilots were asked to rate importance according to a 1 to 5 scale with anchors of trivial for 1 and critical for 5; a non-applicable (N/A) option was also provided.

		Importance				
	N/A	Trivial 1	2	3	4	Critical 5
METAR	○	○	○	○	○	○
PIREPs	○	○	○	○	○	○
PLI	○	○	○	○	○	○
etc.	○	○	○	○	○	○

Table 1: Example of Survey Format (Information Importance)

Section 3 - Use of Current Icing Information Paths: Pilots were asked to "indicate how [they] typically obtain icing information from the paths mentioned". Specific paths through which pilots receive icing information were rated on a scale defined with five anchors, as indicated in Table 2. Since the technology available is highly dependent on the phase of flight, the various paths were evaluated under two phases of flight, namely pre-flight and in-flight phases.

	Never	Rarely	Sometimes	Often	Always
Direct Observations	○	○	○	○	○
PLI	○	○	○	○	○
ATC	○	○	○	○	○
FSS or Dispatch on Radio	○	○	○	○	○
etc.	○	○	○	○	○

Table 2: Example of Survey Format (Frequency of Use of Current Information Paths)

Section 4 - Additional Desired Information and Forecasts: Pilots were asked through a free-response question, to identify additional information they would envision to be useful to help support icing-related decisions.

Section 5 - Information on Significant Aircraft Icing Encounters: This section elicited subjects' exposure to icing conditions in their primary category of operations. The free-response question solicited anecdotal descriptions of significant aircraft icing encounters and was stated as: "Please describe your most significant icing encounter in as much detail as possible".

Section 6 - Key Icing-Related Decisions: Pilots were asked to describe "key icing-related decisions of a typical flight in potential icing conditions". Also, ratings on relative importance of ground versus in-flight icing were collected, according to a five-anchor comparative scale.

Section 7 - Evaluation of Remote Ice Detection System Requirements: Pilots were asked to perform a subjective evaluation of usefulness of potential remote icing detection systems, and queried on sensor minimum useful range and maximum affordable cost.

Survey Distribution

The survey was posted on the worldwide web during a two-month period. A broad range of the pilot community was solicited by electronic mail, electronic newsletter (e.g. AvFlash), web posting (e.g. AvWeb, Bluecoat Digest, aol.com), and other coverage (Business & Commercial Aviation Magazine, 1998). Most of the documented responses were collected within 24 hours following the issue of the AvFlash electronic newsletter. Also, since responses were obtained from subjects who voluntarily self-reported to the survey webpage, results are expected to carry a bias towards pilots who are more computer literate and more interested in icing than the overall pilot population.

Data Analysis

Questions of both multiple-response and free-response types were used throughout the survey. Methodologies for analyzing data compiled in both cases are described below.

Multiple-response questions in Section 2 provided data on ratings of importance of currently available information. Ratings of *4* and above were tabulated and are referred to as "important" in the following. Multiple-response questions in section 3 provided data on ratings of frequency of use of current information paths. Ratings of *often* and *always* were tabulated and are referred to as "frequently used" in the discussion.

Free-response questions were used in sections 4, 5 and 6. Responses in each sections were evaluated by an analyst and grouped according to common responses. Recurring referral to information elements and information products were identified and counts were compiled. Results were reviewed by a second analyst. The methodology is referred below as the recurring-object taxonomy. Narratives on significant aircraft icing encounters collected in section 5 were classified according to impact of aircraft structural icing on operations and escape actions. Results from the General Aviation community were compared with

36 reports collected from the NASA-administered Aviation Safety Reporting System (ASRS) database over an eight-year period (ASRS, 1998). Both analyses were performed using the recurring-object taxonomy. Descriptions of key icing-related decisions collected in section 6 were classified according to two distinct themes: decision type (e.g., go/no-go, avoidance, escape, etc.) and information elements that served as decision criteria (e.g., temperature, visible moisture, etc.).

RESULTS

Section 1 - Response and Scope of Analysis

Data was received from 589 pilots with representation from the operational categories shown in Table 3. Most of the respondents (95%) were instrument-rated pilots. As depicted in Table 3, responses were dominated by general aviation pilots (73%). Due to low response rate from the helicopter community, responses from this subgroup was disregarded in the following analysis. The present analysis hence focuses on results from fixed-wing aircraft pilots only.

Respondents' operations were primarily based in the United States and in Canada (96%). They averaged 3,412 hours of total flight time, 686 hours of instrument time (ranging between an average of 366 hours of instrument time for GA pilots to an average of 3,033 hours of instrument time for major air carrier pilots). Their average age was 44 years old. Only 3% of the respondents were female. A total of 28% of respondents operated aircraft certified for icing.

Operational Category	Primary	Secondary
General Aviation	426	78
Corporate	62	28
Major Air Carrier	39	3
Military Transport	17	4
Commuter Airline	14	5
Military Helicopter	11	2
Military High-Performance	8	5
Civil Helicopter	3	5

Table 3: Respondents' Primary and Secondary Operational Category

Section 2 - Importance of Currently Available Information:

i) Direct Visual Observations, Instruments and Sensors: Figure 1 depicts the percentage of pilots who rated the listed information items as important. Ice accretion was rated important by more than 90% of pilots in all operational categories. Other information elements indicated as important by more than 50% of pilots in each operational categories include temperature (outside air or total) and precipitation. Clouds were indicated as important by a majority of corporate and major air carrier. In most cases, pilots from these groups operate jet aircraft at cruising altitudes above typical cloud deck altitude and procedurally use visible moisture and total temperature below a predetermined value (typically +10°C) as information criteria for activation of the ice protection system.

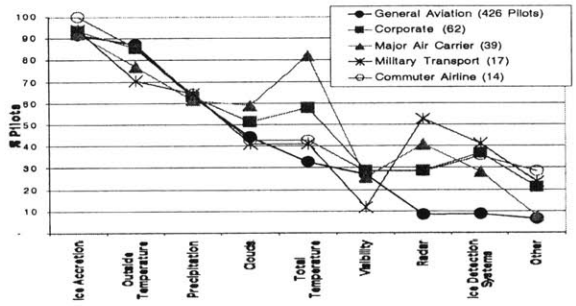

Figure 1: Importance of Direct Visual Observations, Instruments and Sensors

ii) Reported Observations and Measurements: The importance ratings of the reported observations and measurements information elements are presented in Figure 2. PIREPs are dominantly rated important (by over 60%) in all five categories of pilots (with

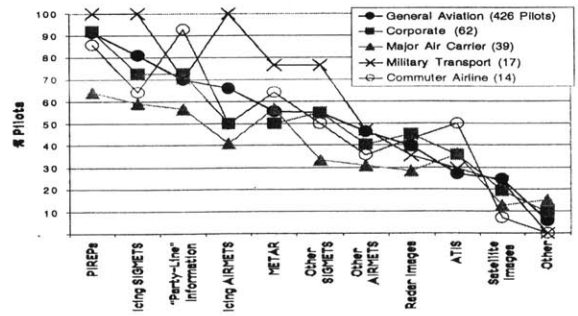

Figure 2: Importance of Reported Observations and Measurements

distribution ranging from 100% for military transport to 64% for major air carrier). Other important types of information indicated as important by over 50% of pilots include icing SIGMETs, "party-line" information and METARs.

iii) Forecasts: The percentages of pilots rating forecasts items as important are presented in Figure 3. Freezing level forecasts are dominant, followed by terminal forecasts (TAF), Area Forecasts (FA), and winds aloft forecasts (FD).

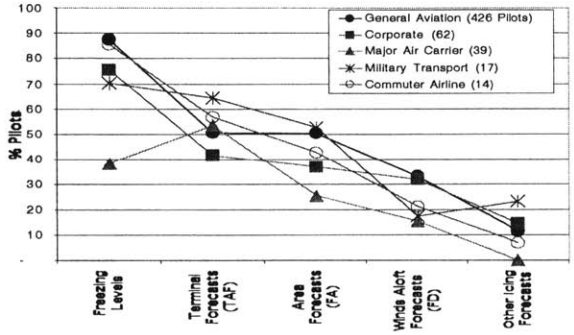

Figure 3: Importance of Forecasts

Section 3 - Use of Current Icing Information Paths

The percentage of pilots who reported frequent use of specific icing information paths in the *pre-flight* phase is depicted in Figure 4. Information collected through the Flight Service Station (FSS), Weather Office and Dispatch, was indicated to be frequently accessed via the phone for commuter, GA and corporate, whereas it was found to be frequently accessed in person by military pilots. Frequent use of direct observations was reported by a significant

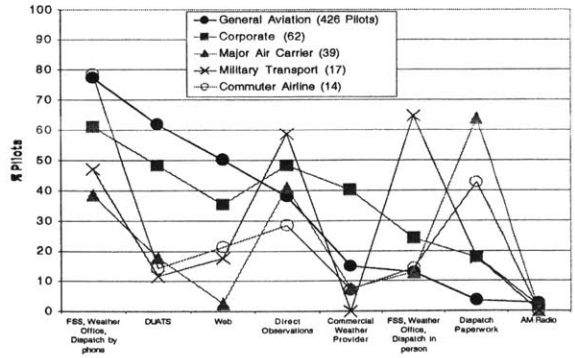

Figure 4: *Pre-Flight* Icing Information Path Use (Frequency)

number of pilots across all operational categories, except for major air carrier and commuter airline pilots, who primarily indicated that they frequently collect icing-related information through dispatch paperwork. Frequent use of the Direct User Access Terminal (DUAT) service was primarily reported by GA and corporate pilots.

Figure 5 depicts the percentage of pilots who reported frequent use of listed *in-flight* icing information paths. As shown, over 75% of pilots in all operational categories indicated that they frequently use direct observations. The next most frequent paths involve voice-transmission and include "party-line" information, communications with ATC, FSS, dispatch and the en-route flight advisory service (EFAS). Airborne sensors are also used by over 30% of pilots in all categories except GA which had a much lower percentage of reported values.

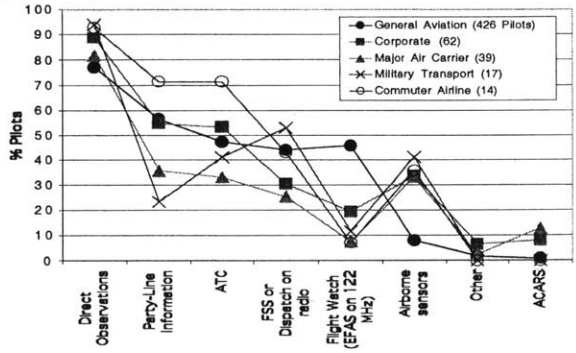

Figure 5: *In-Flight* Icing Information Path Use (Frequency)

Section 4 - Additional Desired Information and Forecasts:

Pilot input was solicited on additional information that would help support icing-related decisions. Major themes emerging from application of the recurring-object taxonomy were the following: desire for improvements to customarily used information such as PIREPs and forecasts; desire for spatial representation of icing location and severity in graphical form; desire for information to be timely.

Section 5 - Information on Significant Aircraft Icing Encounters:

The analysis of the significant encounters by the General Aviation pilots is presented in Figures 6 and 7,

along with the analysis of 36 NASA ASRS icing reports. It should be noted that ASRS reports were initiated by pilots following perceived significant icing encounters, and hence may be biased towards more significant events than those mentioned in the survey. Icing impacts frequently mentioned include difficulty holding altitude and instrumentation problems (e.g., pitot, static or venturi).

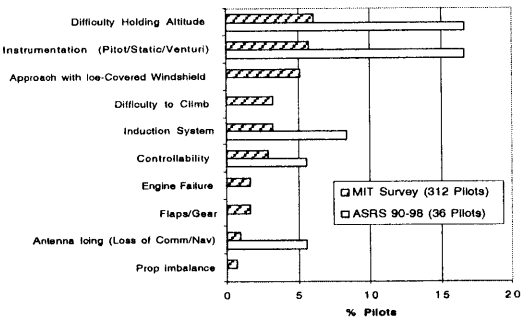

Figure 6: Reported Icing Impact (GA only)

Figure 7 depicts actions undertaken by GA pilots to escape from significant icing situations. As shown, 36% of pilots in the ASRS reports and 13% of pilots in the MIT survey, mentioned diversion to an alternate airport as their chosen escape actions. Descent to altitudes where water droplets do not accrete (warm air) and descent to altitudes featuring visual meteorological conditions (VMC) were also mentioned in large percentages. Maneuvers involving vertical responses (i.e., including either a climb or a descent) accounted for 44% of all ASRS narratives and 12% of all survey responses.

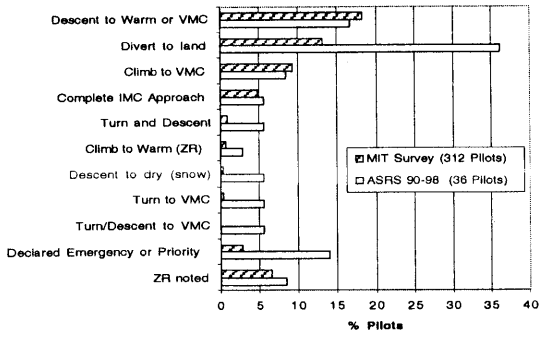

Figure 7: Reported Escape Actions (GA only)

Section 6 - Key Icing-Related Decisions:

Data on key icing-related decisions is presented in Figure 8 for all operational categories. It should be noted that the data is dominated by responses from GA pilots (73%) and pilots flying aircraft not equipped for flight in known icing (72%). As depicted in Figure 8, typical key icing-related decisions included the go/no-go decision, the escape decision, the avoidance decision and the decision of ice protection system management. The dominant criteria used by pilots for making strategic go/no-go decisions was indicated as the possibility to find an escape route. In turn, the evaluation of an optimal escape route involves deciding between actions such as climbing, descending, reversing course or landing at an alternate destination. Avoidance criteria included avoiding visible moisture at temperatures below freezing.

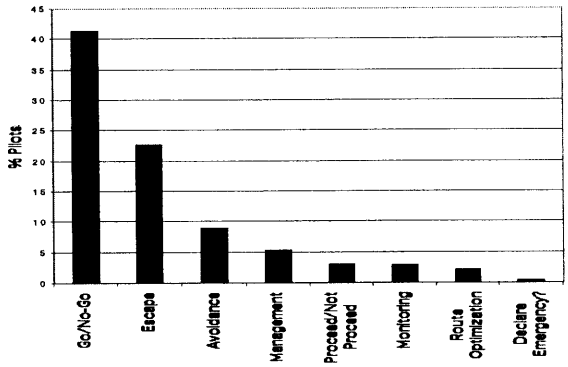

Figure 8: Key Icing-Related Decisions

Key information elements used in the decision-making process were also analyzed with the recurring-object taxonomy and are depicted on Figure 9. Visible moisture, temperature and icing were indicated as primary information criteria.

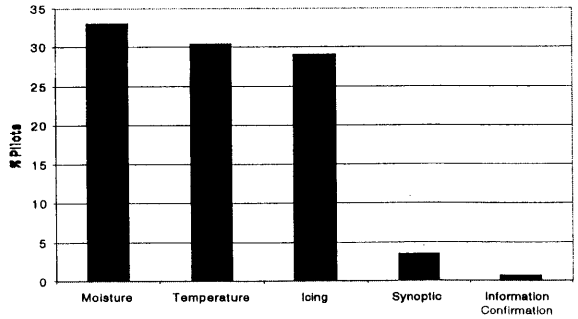

Figure 9: Key Icing-Related Information Criteria

Figures 10 through 12 depict detailed criteria within the moisture, temperature and icing elements. As can be seen in Figure 10, moisture information criteria consist primarily of cloud tops and bases or layer thicknesses and Instrument Meteorological Conditions / Visual Meteorological Conditions (IMC/VMC) boundaries.

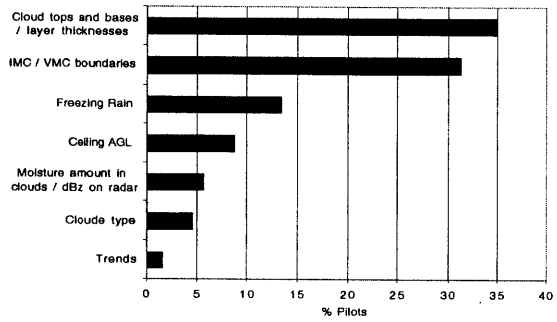

Figure 10: Moisture Information Criteria

As depicted in Figure 11, key temperature criteria include freezing levels, temperature field and local outside air temperature (OAT).

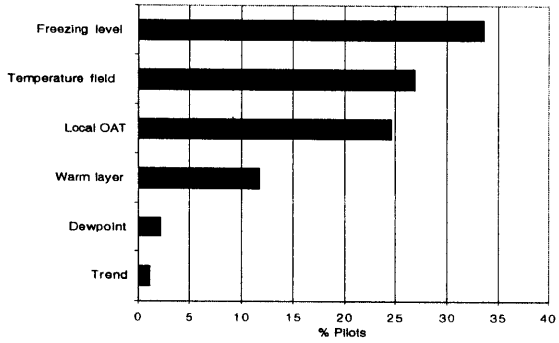

Figure 11: Temperature Information Criteria

Key information criteria directly related to icing are depicted on Figure 12. As can be seen, they primarily include corroborated icing zones based on in-situ information and PIREPs and icing-free zones, spatial extent of the icing conditions (i.e., vertical extent and horizontal extent), as well as type, intensity and probability of icing.

Section 7 - Evaluation of Remote Ice Detection System Requirements:

Pilots rated airborne and ground-based remote sensing systems and datalink technologies as very useful. A majority of pilots in all operational categories indicated a minimum useful range of 40 nm, except for major air carrier. It was found that over 40% of pilots in all categories would pay up to $5,000 for in-flight icing avionics except major air carrier. A lower number of pilots would pay up to $10,000, especially within general aviation (13%).

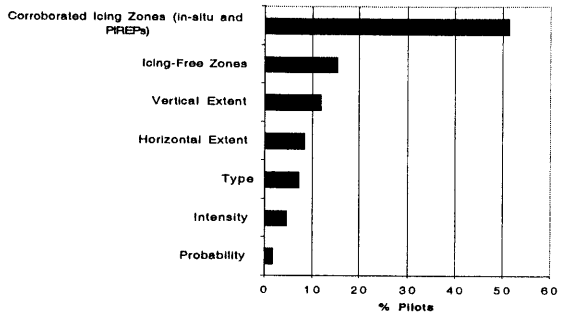

Figure 12: Icing Information Criteria

CONCLUSIONS

The key icing-related decisions identified include: the pre-departure go/no-go decision, escape path selection, penetration versus avoidance of icing conditions, and ice protection system management decisions. For unprotected aircraft, a key criteria in the go/no-go, escape path selection and avoidance decisions was the ability to identify viable escape paths.

Results indicated that key information required to support key icing decisions is the spatial distribution of the icing threat field. Information on accurate spatial location appears to be more important than information on icing severity. The analysis suggested that information on locations where conditions are *not* conducive to icing is perceived as beneficial to support escape decisions.

Because the icing threat field is characterized by a stronger gradient along the vertical dimension, due to typical atmospheric temperature gradients and moisture boundaries, vertical maneuvers were found to be a common strategy to escape from icing conditions. Therefore, remote ice detection systems need to consider sensing and information presentation in the vertical plane.

Information that appears to have the highest credibility involves direct observations by the individual or reported through PIREPs. These in-situ observations are nevertheless limited both spatially and temporarily. Hence, there does appear to be a need for remote ice detection to improve the spatially and temporarily identification of icing conditions.

Survey responses (dominated by GA pilots) indicated the maximum cost the GA market will bear for remote ice detection is on the order of $5,000. Because it will be difficult to produce equipment at such a cost level, the most likely use of remote ice detection will be in ground-based systems to support "nowcasting" and forecasting of icing conditions.

ACKNOWLEDGEMENTS

This work was supported by the National Aeronautics and Space Administration / Glenn Research Center under grant NAG3-2178. The authors also wish to acknowledge the collaboration of the numerous pilots who contributed to this work by sharing their experience through the completion of the survey.

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APPENDIX D – EXPERIMENT ON INFLUENCE OF ICING INFORMATION ON ROUTING DECISIONS

Vigeant-Langlois, L. & R.J. Hansman, 2000: Influence of icing information on pilot strategies for operating in icing conditions. Journal of Aircraft, American Institute of Aeronautics and Astronautics, Vol. 37, No. 6., pp. 937-946.

JOURNAL OF AIRCRAFT
Vol. 37, No. 6, November-December 2000

Influence of Icing Information on Pilot Strategies for Operating in Icing Conditions

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The influence of potential remote ice-detection system features on pilot decision making was investigated through a Web-based experiment. Display features including a graphical plan view depiction of icing severity, vertical view depiction, single and multiple icing severity levels as well as sensor range were varied in a part-task simulation experiment. Using information from each display, pilots were presented with a set of four flight scenarios and probed on their routing decisions and comfort level with those decisions. The experiment also included a subjective display preference evaluation. Results show that all of the displays improved pilot decision making over existing text-based icing information. The three-dimensional displays that included vertical depiction of icing conditions were found to support improved decision making. Range was not found to be a strong factor in the experiment; however, the minimum range tested was 25 n miles, which may be in excess of current technical capabilities. The depiction of the severity of icing conditions was not found to be as important as accurate information on the location of icing conditions.

Introduction

TO investigate the influence of display features of potential remote ice-sensing systems on pilot decisions, a Web-based experiment was conducted. The study was ultimately aimed at providing functional requirements for the development of remote sensing and forecasting systems[1-4] consistent with an integrated human-centered system approach.[5] Icing information issues identified in a prior survey[6] were investigated in test scenarios that focused on tactical en-route decisions in icing weather situations. Features of cockpit icing information systems were manipulated as independent variables in this experiment, and pilot routing decisions and comfort levels were analyzed.

Objectives

The objective of this experiment was to investigate the impact of selected display features of potential icing remote detection systems on pilot decision making. The experiment was designed to investigate how remotely sensed icing information, presented in graphical form, could support pilot decision making when operating in icing conditions.

Icing remote sensing display features of interest were identified to include range, the presence of a vertical display, and single vs multiple levels of icing severity. Spatial range is of interest because sensors being considered for icing remote sensing have different range and scanning capabilites.[1] Prior studies have indicated that pilot strategies for operating in icing conditions often include vertical escape and avoidance maneuvers[6]; therefore, the influence of a vertical view was investigated.

The third display feature tested was single vs multiple levels of icing severity. Because the problem of accurately detecting the expected severity of an icing encounter is significantly more difficult than simply identifying the spatial location where icing can occur, an attempt was made to investigate the benefit of depicting multiple severity levels. The reason why spatial location can be more easily detected is that it is often easier to identify the areas where icing conditions are not present based on either lack of visible moisture (e.g., which can often be detected by satellite remote sensing) or regions where temperatures are above the freezing level. Another issue with icing severity is that the ice impact can vary between aircraft flying through the same meteorological conditions as a result of air speed and geometric effects. This phenomenon makes inference of icing severity difficult from pilot reports (PIREPs) and other sources.

In considering the display issues just mentioned, the experiment attempted to address the questions listed next:

1) How would remotely sensed icing information support pilot decision making when operating in icing conditions?

2) How would fundamental display features of icing remote-sensing systems influence pilot decision making in operations in icing conditions? More specifically, what is the influence of display spatial coverage, the provision of a profile display, and the number of levels of severity of icing information on pilot decisions?

3) How would pilots' confidence in their decisions vary according to the icing information presented? How does it relate to the quality of pilots' decisions?

4) Does icing-related graphical information impact pilot decisions differently depending on the level of ice protection?

Method

A part-task experiment probing fundamental icing remote sensing display features was conducted, using a testable response method[7] to evaluate decision quality and pilots' situation awareness of icing conditions. This subsection provides an overview of the experimental method employed. First, the set of independent variables used in the experiment is presented. The five prototype icing remote-sensing displays used in the experiment are subsequently described. A description of the dependent experimental variables is provided, followed by a description of the design of the four experimental flight scenarios.

Independent Variables

The experiment used two independent variables including the features of the icing display and the level of ice-protection equipment on the aircraft. To study the effect of display features on pilot rerouting decisions, selected features were varied in the five prototype displays shown in Fig. 1. Display A provided textual information only, based on surface observations and PIREPs, when available, and hence served as a baseline display. The most enhanced icing display, display E, had a maximum range of 50 n miles with both horizontal and vertical depictions of icing conditions. Icing conditions were

Presented as Paper 2000-0365 at the AIAA 38th Aerospace Sciences Meeting, Reno, NV, 10-13 January 2000; received 10 February 2000; revision received 28 June 2000; accepted for publication 2 July 2000.

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Table 1 Legend of displays depicting multiple levels of icing severity

Severity level	Color	Criteria	Definition
No icing	Black	No signal return	—
Trace	Green	LWC < 0.1 g/m^3 and T < 2°C	Ice becomes perceptible. Rate of accumulation is not hazardous even when no ice-protection system is utilized, unless encountered for over 1 h.
Icing	Yellow	0.11 < LWC < 1.2 g/m^3 and T < 2°C	Light and moderate ice accretion. The rate of accretion is potentially hazardous without ice-protection systems, and over extended period of time even with the utilization of ice-protection system.
Severe icing	Red	LWC > 1.2 g/m^3 or large drops and T < 2°C	The rate of accretion is such that ice-protection equipment fails to reduce or control the hazard. Immediate diversion is necessary.

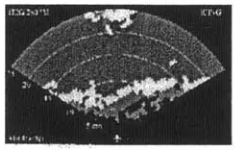
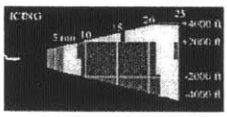
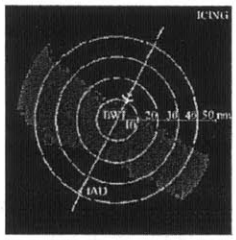
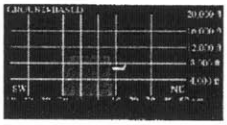
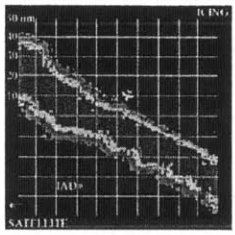
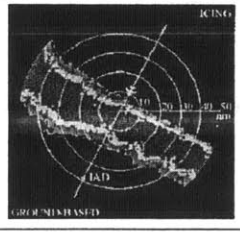
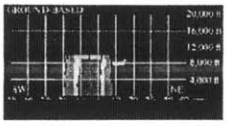
Display	Name in Web-Based Experiment	Graphical Representation	Sensor Range [nm]	Vertical View	Type of Icing Info.
Display A	Textual Information	×	×	×	×
Display B (3D, min range, 3 levels)	Airborne Icing Severity System		25 Min. Range		Icing Severity 3 Levels
Display C (3D, max range, 1 level)	Ground-based Icing Presence System		50 Max. Range		Icing Presence 1 Level
Display D (2D, max range, 3 levels)	Satellite-based Icing Severity System		50 Max. Range	×	Icing Severity 3 Levels
Display E (3D, max range, 3 levels)	Ground-based Icing Severity System		50 Max. Range		Icing Severity 3 Levels

Fig. 1 Display feature matrix. (Actual displays are in color. Displays B, D, and E depict three levels of icing severity as green, yellow, and red; display C depicts one level of icing as blue.)

displayed in three levels: severe, icing, and trace described in Table 1. Each of the other displays had less enhanced features than display E in one area. Display B had a range limitation of 25 n miles or half the range of display E to allow investigation of the effect of sensor range. Display C had only one level of icing (i.e., icing presence). This allowed investigation of the impact of providing icing severity diagnostic information. Display D did not have a vertical depiction to allow evaluation of the effect of a vertical display.

For the subject pilots to be able to discriminate between the different displays, each display was related to a hypothetical remote sensing system or platform, which could support the display features. The most enhanced display, display E, was identified as a ground-based icing severity system. As shown in Fig. 1, the other displays, A, B, C, and D, were referred to as textual information, airborne icing severity system, ground-based icing presence system, and satellite-based icing severity system, respectively. These

Table 2 Legend of display C (three-dimensional, max range, one level)

Icing level	Color	Criteria	Definition
No icing	Black	T > 2°C or outside clouds	Based on signal returns; black zones within the system range correspond to locations where atmospheric conditions are not conducive to aircraft structural icing.
Icing	Blue	No return	Blue areas are by default areas where weather conditions may be conducive to aircraft icing; no severity index depiction is enabled.

designations were simply used to ease the identification of the display and do not imply the existence of such sensor systems.

A detailed description of the icing information presented on displays B, D, and E was provided to subjects in the prescenario briefing section of the experiment. The color-coded severity levels were defined according to the definitions provided in the Airmen Information Manual.[8] A set of physical criteria based on liquid water content (LWC), drop size, and temperature (T) ranges was also provided. Green was defined to induce trace icing, based on LWC less than 0.1 g/m^3 and temperature below 2°C. Red was defined to include severe icing, based on LWC greater than 1.2 g/m^3 and temperatures below 2°C, or large drops and temperatures below 2°C. Yellow was defined to include icing based on criteria between the trace and severe ice definitions. Black corresponded to no measured signal and hence no detected icing conditions.

Display A (Text Only)

Display A provided textual information only. Information was based on reported airport surface observations, conditions observable in flight, and PIREPs, when available. It served as baseline information that would correspond to information currently available in the cockpit nowadays. The same textual information was also provided with all of the graphical displays.

Display B (Three-Dimensional, Min Range, Three Levels)

Display B (three-dimensional, min range, three levels) featured an aircraft-centered perspective and reduced horizontal and vertical ranges in comparison to the ground-based system. An example of depiction of icing conditions by display B is shown in Fig. 2. The forward range was restricted to 25 n miles, the angular range set to 120 deg (similar to an airborne weather radar). With a vertical angular range of 6 deg, the vertical coverage at maximum forward range was 8000 ft (2438 m).

Display C (Three-Dimensional, Max Range, One Level)

Display C only depicted ice presence and used a different color coding. A detailed description of the legend for display C was provided to the test subjects in the prescenario briefing and is shown in Table 2.

Display C measurements were based on the detection of conditions not conducive to aircraft icing such as temperature and cloud detection (although the details were not provided). Black corresponded to these areas, and blue, by inference, corresponded to areas where icing was possible.

An example of depiction of icing conditions by display C (three-dimensional, max range, one level) is shown in Fig. 2. The plan-view display was centered at Baltimore–Washington International Airport (BWI), provided a 50 n miles range in a North-up coordinate frame and depicted 10 n miles range rings centered at BWI. The vertical-view display was also centered at BWI and provided a 20,000-ft (6096-m) vertical coverage. The test subject's own aircraft position and destination, Washington Dulles International Airport (IAD), were also depicted on both displays.

Display D (Two-Dimensional, Max Range, Three Levels)

Display D (two-dimensional, max range, three levels) mainly differed from the most enhanced display, display E by the lack of a vertical depiction. An example of depiction of icing conditions by display D is shown in Fig. 2.

Display E (Three-Dimensional, Max Range, Three Levels)

Display E (three-dimensional, max range, three levels) was the most enhanced system and had a range of 50 n miles. An example of depiction of icing conditions by display E is shown in Fig. 2.

Ice-Protection Equipment Level

With regard to icing, flight operations have different operating rules according to whether or not the aircraft is certified for flight operations in known icing conditions, as defined by the Federal Aviation Regulations, Part 25, Appendix C.[9] Aircraft are not certified for flight in severe icing conditions, which are outside of the Part 25, Appendix C envelope. These include large droplets and high LWC conditions.

Aircraft that are not certified are not approved for operations in known icing conditions and need to avoid or escape from all levels of icing conditions. Because the icing restriction is based on the demonstration of aircraft operations with specified ice-protection equipment, operations under such restrictions are referred to, throughout this document, as nonequipped operations. In turn, known icing approved operations are termed ice-protection equipped operations, or equipped operations.

Based on whether they typically flew with ice-protection equipment, each pilot in the experiment was assigned to an equipped or nonequipped group. For the experiment, the equipped pilots were given a light twin-engine aircraft that was equipped and certified for flight into known icing conditions and the nonequipped group was given a similar aircraft without ice protection equipment.

Dependent Variables

To probe the influence of the various display features, data were collected for each event on pilot tactical rerouting decisions and comfort levels; a free-response question also probed the pilots' rationale behind their rerouting decisions. In completing the experiment, pilots were also asked to indicate their relative preference for each display.

For each flight event the first question was stated as, "What is your decision?" Pilots indicated their routing or rerouting decision in a multiple-response field. Figure 3 (top) shows an example of a pilot's decision to perform a 30-deg-lateral deviation to the left and a climb to 10,000 ft. The bottom portion of Fig. 3 shows the complete set of decision options provided in the multiple-response field. As shown, pilots could choose from a discrete set of cruising altitudes for flights under instrument flight rules when headed in a westerly direction and ranging between the stated minimum en route altitude of 3000 ft (914 m) and the indicated aircraft maximum ceiling of 15,000 ft (4572 m).

Each routing decision was rated according to a decision quality rating scheme. In each flight scenario a set of good, acceptable, and poor decisions has been identified based on optimal strategic routing for pilots with full situation awareness. This experimental approach, based on the testable response method,[7] provided means to rate pilots' response based on optimal situation awareness criteria and hence to determine the influence of information presentation on pilot decision.

Flight Scenario Design

Using each of the five display systems, pilots were exposed to a set of four icing-intensive scenarios: 1) warm front avoidance; 2) embedded convective weather avoidance; 3) visual meteorological conditions (VMC)-on-top avoidance; and 4) stable layer escape. As indicated by their names, three of the four flight scenarios consisted

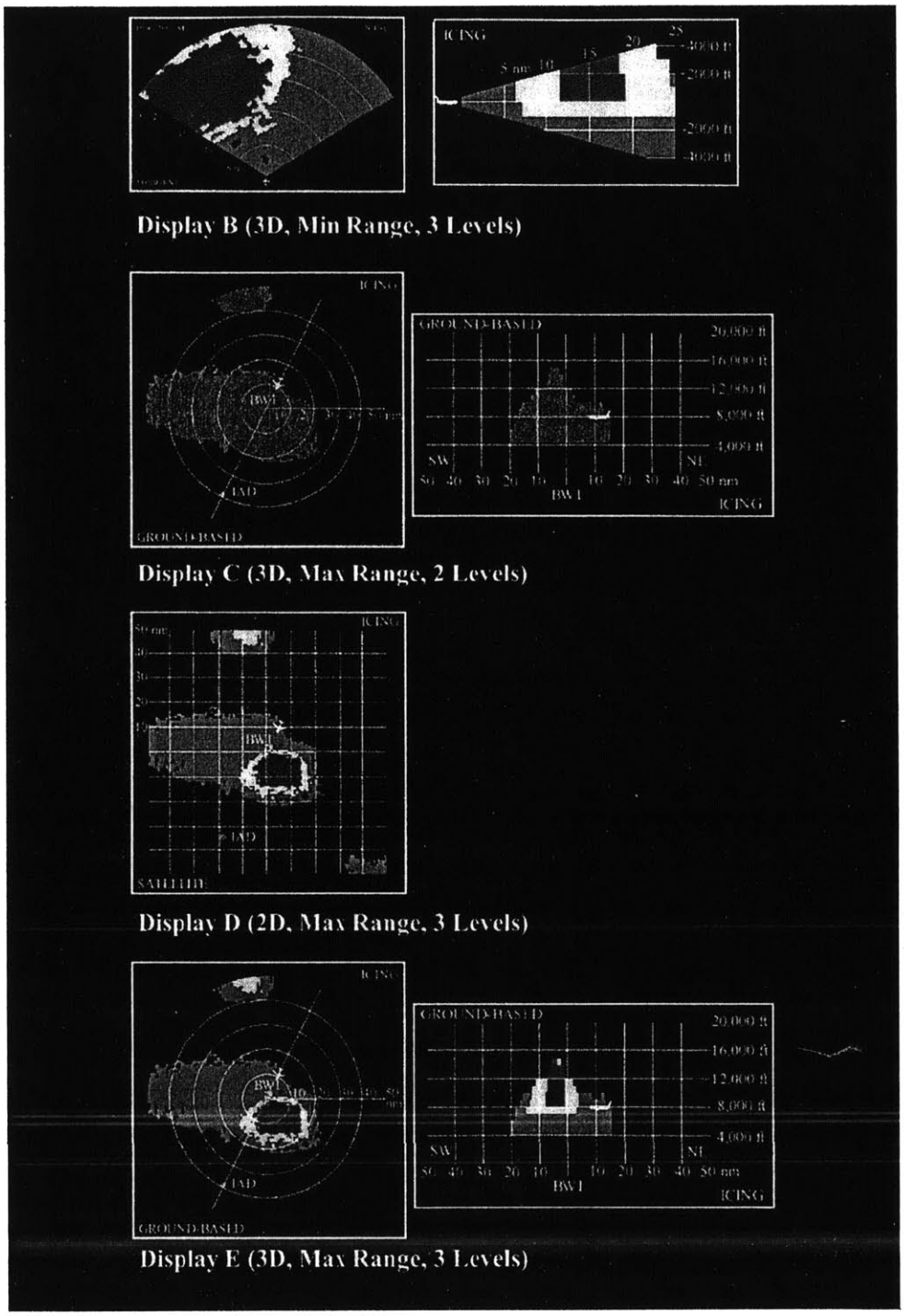


Fig. 2 Displays B–E depicting icing conditions in scenario 2 (black, no icing; green, trace; yellow, icing; red, severe icing; blue, icing—all severities).

of penetration-vs-avoidance situations, whereas one of the scenarios involved a situation of immersion in icing conditions where an escape maneuver is necessary. Each test subject hence went through a set of 20 events. A description of the operational constraints involved in each flight scenario is provided in the following paragraphs.

Prior to starting the experiment, pilots were given a preflight briefing, which stated that all flight scenarios would start at the same geographical location, that is, 50 n miles from the destination, Washington Dulles airport (KIAD), and they would be heading toward Baltimore (KBWI), which was located 10 n miles ahead along the planned route. The distance from neighboring radio-navigational aids and airports, including Philadelphia (KPHL), was also provided. As just mentioned, the aircraft maximum ceiling was given to be 15,000 ft (4572 m), and the minimum en-route altitude was 3000 ft (914 m).

Scenario 1: Warm Front Avoidance

In this flight scenario pilots were presented with a situation involving a warm front intersecting with the planned route. Observable conditions outside the window were instrument meteorological

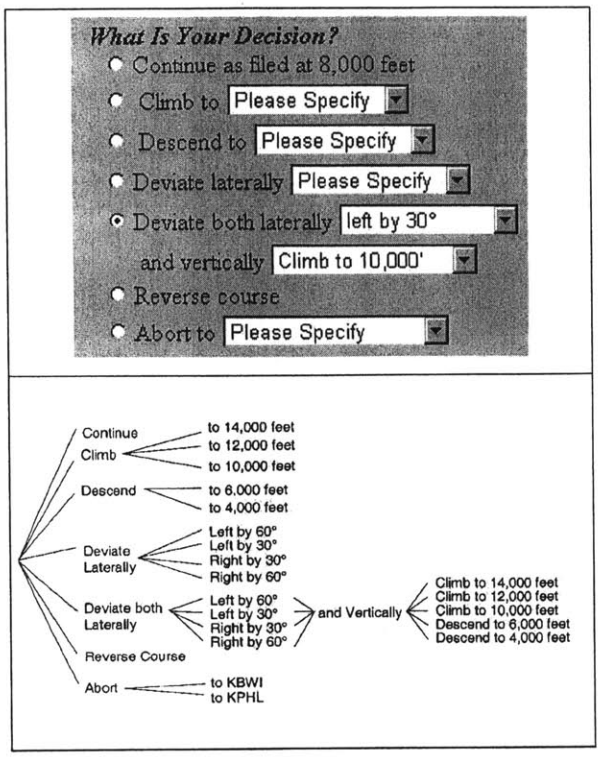


Fig. 3 Pilot selected routing decision (top) and routing decision tree (bottom).

conditions (IMC), and the outside air temperature (OAT) probe indicated +1°C. Freezing rain was reported at KBWI. Surface observations were also provided at three neighboring airports: KPHL reported an overcast conditions at 15,000 ft (4572 m), a temperature of −4°C and a dewpoint of −10°C; KBWI reported overcast conditions at 200 ft (61 m), freezing rain, a temperature of −3°C and a dewpoint of −4°C; KIAD reported scattered conditions at 2000 ft (610 m), a temperature of −2°C, and a dewpoint of −3°C. No PIREP was reported so that there was no indication of the altitude at which the freezing precipitation could be overflown.

Figure 4 shows the presentation of weather conditions on all displays in scenario 1. With optimal situation awareness of the conditions, the expected rerouting decision was for the pilots to top the freezing precipitation and continue toward destination.

Scenario 2: Embedded Convective Weather Avoidance

This flight scenario was set in IMC where convective cells were embedded in stratus clouds. The aircraft had entered an area where conditions may have been conducive to trace icing. Observable conditions were IMC. The aircraft had recently experienced light-to-moderate chop at the cruising altitude, and embedded cumulus clouds were expected. The OAT probe indicated +2°C, and there was no observation of ice accretion. A light twin-engine aircraft cruising at 8000 ft (2438 m) and 25 n miles west of the subject aircraft location had recently reported a PIREP of moderate icing and an OAT of 0°C. The surface observations at neighboring airports reported the following conditions: overcast at 3000 ft (914 m) at KPHL, temperature of 7°C, dewpoint of 4°C; BWI reported overcast conditions at 3000 ft (914 m), a surface temperature of 8°C, and a dewpoint of 6°C; KIAD reported overcast conditions at 4000 ft (1219 m), a surface temperature of 8°C, and a dewpoint of 6°C.

Figure 4 shows the presentation of weather conditions on all displays in scenario 2. Distinct behaviors were expected for pilots of nonequipped and equipped operations. With optimal situation awareness it was expected that pilots would opt for a descent to 4000 ft (1219 m). Lateral deviation to the right of the planned course was also considered good for equipped operations. Particular attention was given in the design of the scenario to provide a basis for testing the influence of icing presentation on the preference between vertical and lateral rerouting in the latter type of flight operations.

Scenario 3: VMC-on-Top Avoidance

This flight scenario was set in VMC. Weather along the planned route of flight was such that the aircraft was about to overfly a progressively raising cloud deck located approximately 1000 ft (305 m) below.

This layer of clouds had conditions conducive to aircraft icing. The aircraft was projected to penetrate the icing conditions unless rerouting was initiated. The outside air temperature indicated 0°C, and no ice accretion had been observed. A PIREP had been given 10 n miles further along the planned route: a light twin-engine aircraft descending through 6000 ft (1829 m) had reported moderate icing and an outside air temperature of −1°C.

The surface observations at neighboring airports reported the following conditions: KPHL reported overcast conditions at 4000 ft (1219 m), temperature of 9°C, and dewpoint of 6°C; KBWI reported overcast conditions at 3000 ft (914 m), surface temperature of 10°C, and dewpoint of 6°C; KIAD reported overcast conditions at 4000 ft (1219 m), surface temperature of 10°C, and dewpoint of 6°C.

Figure 4 shows the presentation of weather conditions on all displays in scenario 3. With optimal situation awareness pilots were expected to descend to 4000 ft (1219 m) and proceed to destination.

Scenario 4: Stable Layer Escape

This flight scenario took place in IMC, where conditions were conducive to airframe icing; it was hence referred to as an escape scenario. The subject aircraft had just started to accumulate light-to-moderate ice accretion. No PIREP had been reported.

The surface observations at neighboring airports reported the following conditions: KPHL reported overcast conditions at 3000 ft (914 m), a temperature of 0°C, and a dewpoint of −3°C; KBWI reported overcast conditions at 2000 ft (610 m), a temperature of 1°C, and a dewpoint of −3°C; KIAD reported scattered conditions at 2000 ft (610 m), a temperature of 1°C, and a dewpoint of −2°C.

Figure 4 shows the presentation of weather conditions on all displays in scenario 4. With optimal situation awareness it was expected that pilots would escape the icing conditions by climbing above 9000 ft (2743 m) and proceed toward destination.

Experimental Protocol

The experiment was posted on the Web during the month of July 1999. A broad range of the pilot community was solicited by electronic mail, electronic newsletter (e.g., AvFlash), and Web posting (e.g., AvWeb, Bluecoat Digest, aol.com, IAOPA Website). Counterbalancing was performed by rotating the order of display and flight scenario presentations between subjects, based on five types of subjects. Because of the considerable duration of the experiment (approximately 45 min to complete), not all potential test subjects who started the experiment actually completed it. Only the scripts that were complete are included in the analysis. Because responses were obtained from subjects who voluntarily self-reported to the survey Webpage, results are expected to carry a bias toward pilots who are more computer literate and more interested in icing issues than the overall pilot population.

Analysis of Pilot Routing Decisions

For each scenario and level of ice-protection equipment, a three-level decision rating scheme (classifying good, acceptable, and poor decisions) was prepared by two analysts.

The decision space was first evaluated according to whether the subsequent aircraft routing or rerouting maneuver would lead to penetration of trace, icing, or severe levels of icing conditions. The quality of the decision was evaluated independently of the display used. Based on the icing severity level projected to be penetrated according to indicated rerouting maneuvers, the decisions were rated as good, acceptable, or poor decision, according to safety and efficiency considerations.

For pilots of the equipped group, the evaluation was performed as follows. If the aircraft were projected to penetrate into severe

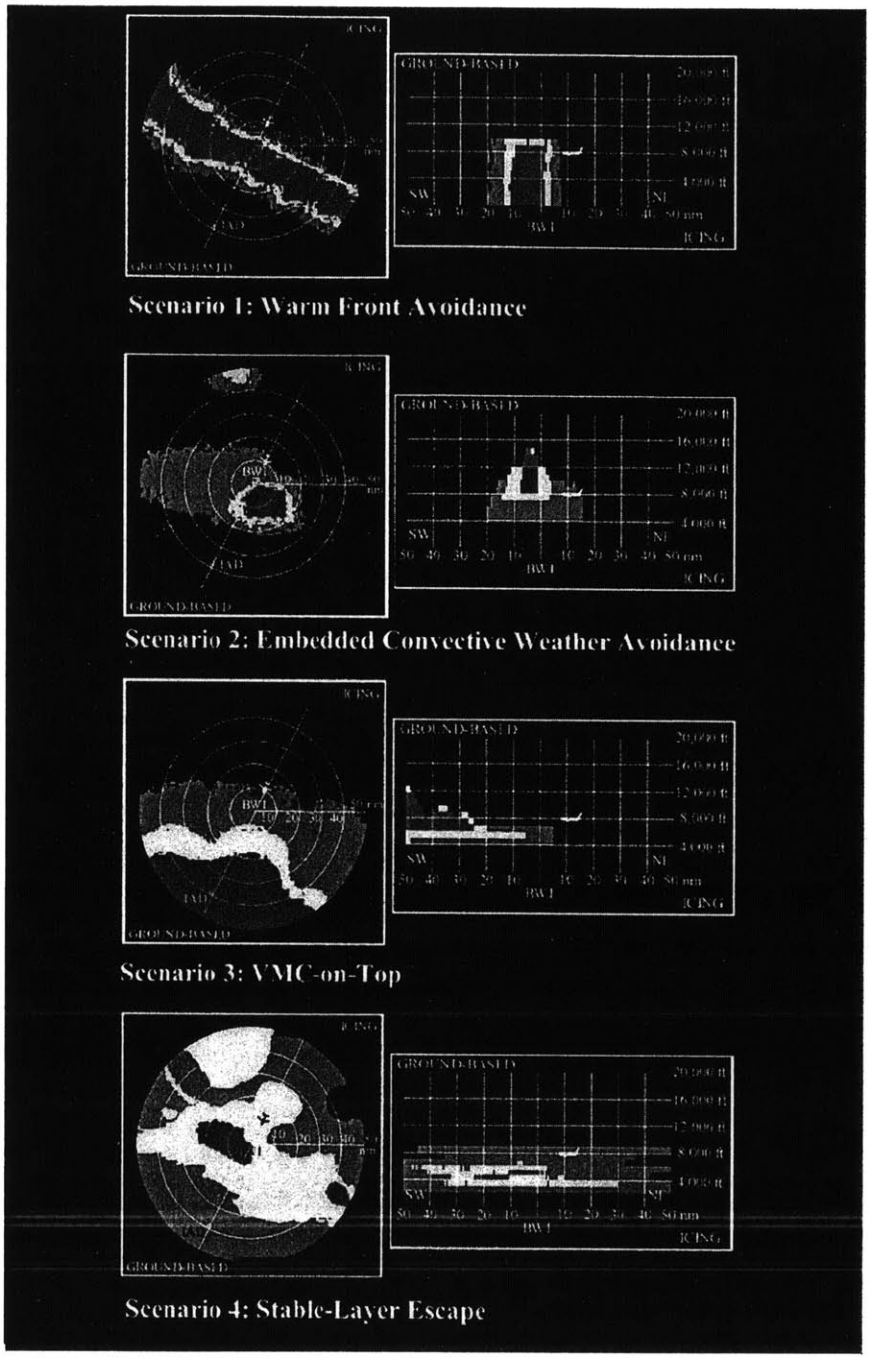


Fig. 4 Depiction of icing conditions in all four scenarios (black, no icing; green, trace; yellow, icing; red, severe icing).

icing conditions, the decision was rated as poor. If the aircraft were projected to penetrate into trace icing with a nonoptimal routing or if it were projected to abort the flight or reverse course safely, the decision was rated as acceptable. If the decision corresponded to an optimal icing avoidance or escape maneuver, it was rated as good. For projected trajectories at the boundary of conditions of distinct severity levels, the more conservative rating was applied.

For the nonequipped group the evaluation was performed based on more conservative criteria. In avoidance cases if the aircraft were projected to enter any level of icing conditions, the decision was rated as poor. If the decision led to optimal avoidance or escape, it was rated as good. If the decision involved an escape maneuver with somewhat more than minimal exposure to trace icing but no exposure to higher levels, it was rated as acceptable. For projected trajectories at the boundary of conditions of distinct severity levels, the more conservative rating was applied, except if it were at a minimal altitude where no icing conditions were depicted at airports and in an area where it is possible to abort.

Results

Response and Background Information

A total of 230 complete and valid responses were used in the Web-based experiment analysis. Statistical information of test subjects is presented in Table 3. As shown, pilots who typically operated known icing-certified aircraft had considerably more flight experience and

Table 3 Subject experience

Operational category	Total time, h	Instrument time, h	Age	Sex, % male	Commercial, %	Airline transport pilots, %	Instructor, %	Instrument, %	Average X-C range, n mile
Certified	9494	2062	48	98	38	72	48	91	698
Noncertified	1407	302	40	97	15	10	16	84	337

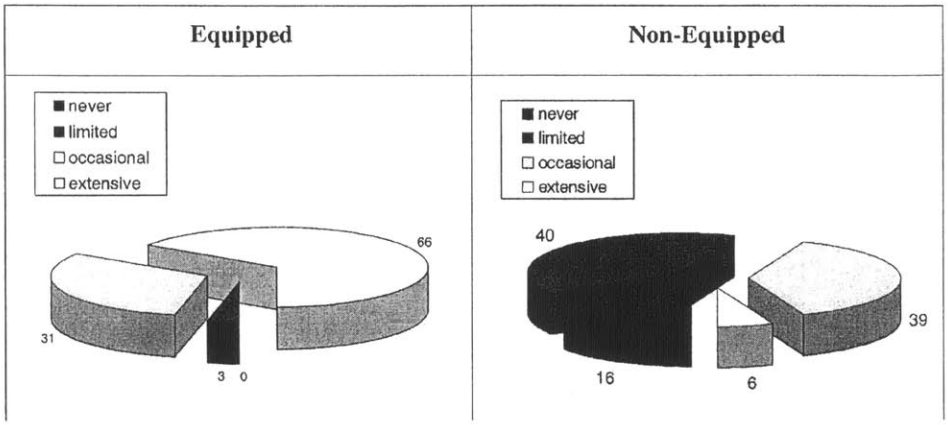


Fig. 5 Subjects' reported experience in icing conditions.

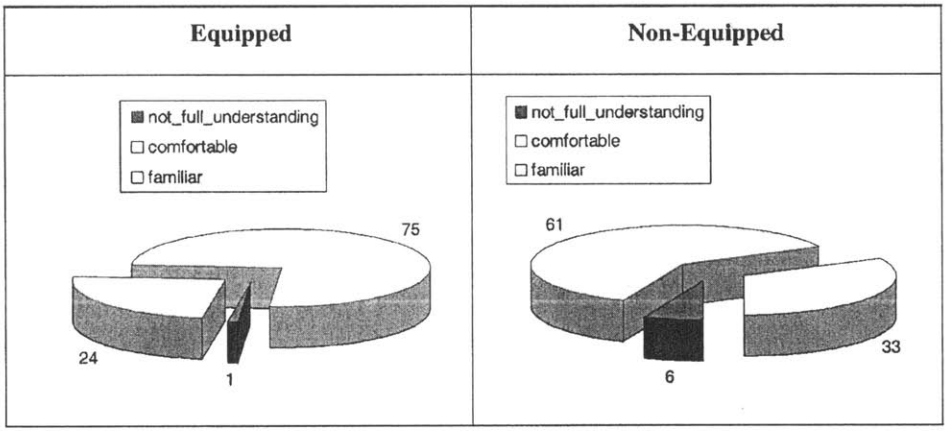


Fig. 6 Subjects' reported understanding of aircraft icing.

qualifications than pilots of aircraft not certified for flight into known icing.

Figures 5 and 6 present the distribution of subjects' icing experience and understanding of issues associated with airframe icing, respectively. As can be seen, equipped pilots had significantly more experience and familiarity with issues relating to in-flight icing rather than nonequipped pilots.

Routing Decisions

Pilot decision quality was evaluated based on the routing decisions they indicated in each flight scenario. Results averaged over all flight scenarios are presented in Fig. 7.

When provided with only textual icing information, pilots indicated more willingness to continue as filed in hazardous icing conditions compared to with graphical displays. This was particularly true in scenarios 1 and 3. When the pilots elected to maneuver with textual information only, they were more likely to reverse course or abort than to elect either lateral or vertical deviations.

When provided with information from the limited-range display B (three-dimensional, min range, three levels), pilots were observed to optimize near-term (tactical) rather than strategic routing. The appropriateness of such decisions was observed to depend on the spatial extent of the icing threat field. For example, equipped pilots using display B performed well in the embedded convective weather scenario, scenario 2, with 91% good decisions. Conversely, in the VMC-on-top scenario, scenario 3, pilots performed poorly (96% of equipped pilots and 82% of nonequipped pilots) with display B.

When provided with information from the single-severity-level depiction display C (three-dimensional, max range, one level), pilots tended to select rerouting decisions involving minimal exposure to the icing conditions. This was observed in scenarios 2 and 3.

When provided with information from the two-dimensional display D (two-dimensional, max range, three levels), a consistent preference for horizontal maneuvers over vertical maneuvers was observed in comparison with the most enhanced display, display E (three-dimensional, max range, three levels).

Pilots using the most enhanced display, display E (three-dimensional, max range, three levels), were observed to have the smallest number of poor decisions. This percentage reached only 9% for equipped pilots and 22% for nonequipped pilots.

The only significant overall difference between pilots of equipped and nonequipped operations appeared to be that the latter group was more likely to abort or reverse course.

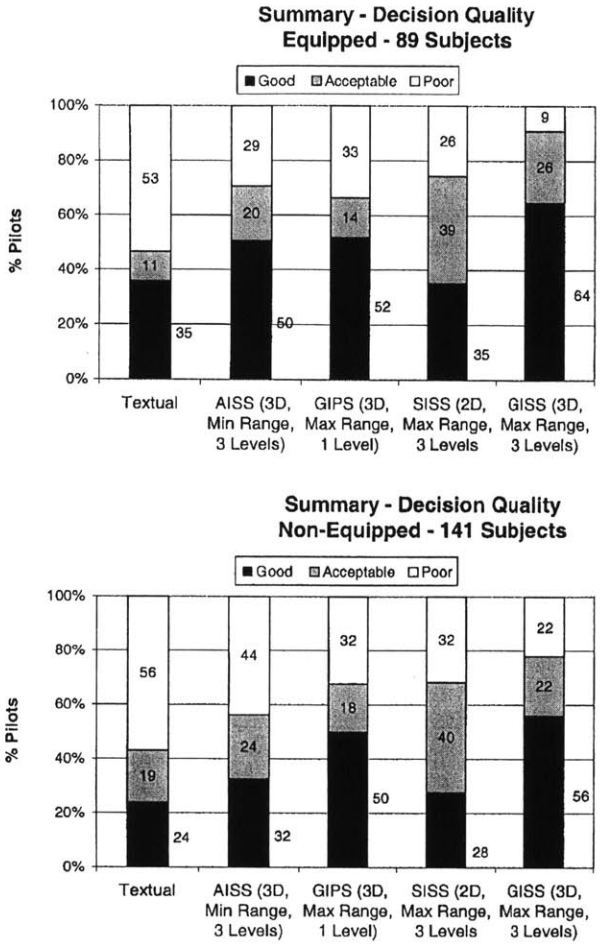


Fig. 7 Pilots' decision quality across all flight scenarios.

Decision Comfort Levels

Pilots were queried on their comfort level after making each decision. The results for equipped and nonequipped pilots averaged over all four scenarios are shown in Fig. 8.

The summary results show that fewer nonequipped pilots indicated that they were either comfortable or very comfortable in making their routing or rerouting decisions. Results also show that pilots indicated higher comfort levels when support information from the most enhanced display, display E (three-dimensional, max range, three levels) was available, and lower comfort levels when only textual information was available.

Correlation Analysis Between Decision Quality and Comfort Level

To test the strength of the association between the decision quality and comfort level, a simple correlation analysis was performed using the sample correlation coefficient.[10] Overall, very little linear correlation was found between the two distributions. The highest correlation coefficient between pilots' decision quality and comfort level was found in scenario 1 with the use of display D (two-dimensional, max range, three levels) for equipped operations and had a value of 0.33. A majority of coefficients were lower than 0.1.

Because this result was unexpected, further care was given in characterizing the relationship between indicated comfort level and decision quality. The lack of correlation can be seen in Fig. 9.

The top plot corresponds to results from pilots of equipped operations, and the bottom plot corresponds to results from pilots of non-equipped operations. Overall, pilots of nonequipped operations were less comfortable in making their routing decisions, which correlates with pilots' flight and icing experience.

Table 4 Display preference ratings (equipped)

Display	A (text only)	D (2D,[a] max range, three levels)	C (3D,[b] max range, one level)	E (3D, max range, three levels)	B (3D, min range, three levels)
A	1	40	38	40	26
D	——	1	1	8	9
C	——	——	1	10	6
E	——	——	——	1	2
B	——	——	——	——	1

[a]Two-dimensional. [b]Three-dimensional.

Table 5 Display preference ratings (nonequipped)

Display	A (text only)	D (2D,[a] max range, three levels)	C (3D,[b] max range, one level)	B (3D, min range, three levels)	E (3D, max range, three levels)
A	1	129	128	Infinity	Infinity
D	——	1	2	9	13
C	——	——	1	5	20
B	——	——	——	1	1
E	——	——	——	——	1

[a]Two-dimensional. [b]Three-dimensional.

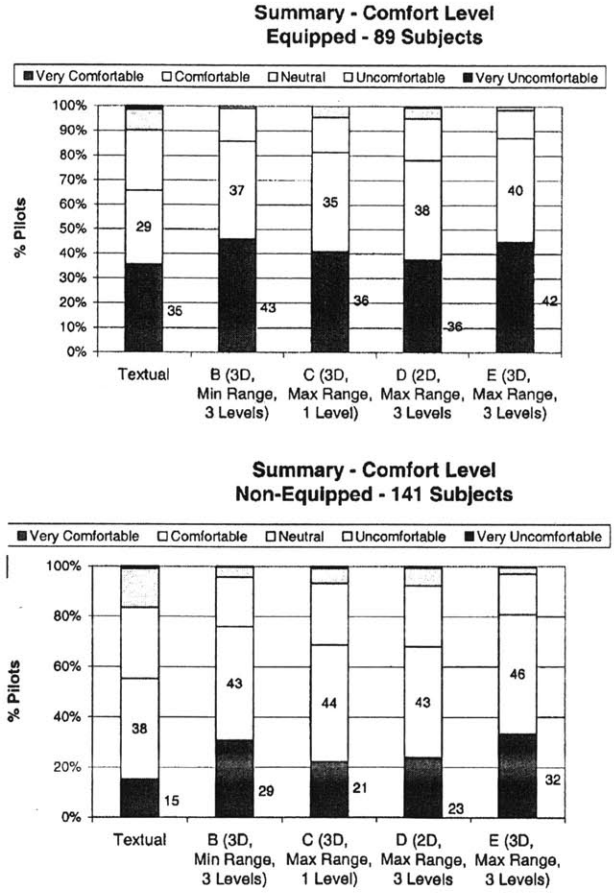


Fig. 8 Pilots' reported comfort levels across all flight scenarios.

Subjective Display Comparison

Results of pilot subjective ratings of relative display preferences are presented in Tables 4 and 5. Each cell corresponds to the ratio of the number of pilots who preferred the displays along the rows to the displays along the columns.

In both tables displays are ranked according to their indicated preference. Each cell indicates the dominance ratio for the column display over the row display. For example, display C (three-dimensional, max range, one level) was preferred 38 times over display A (text only).

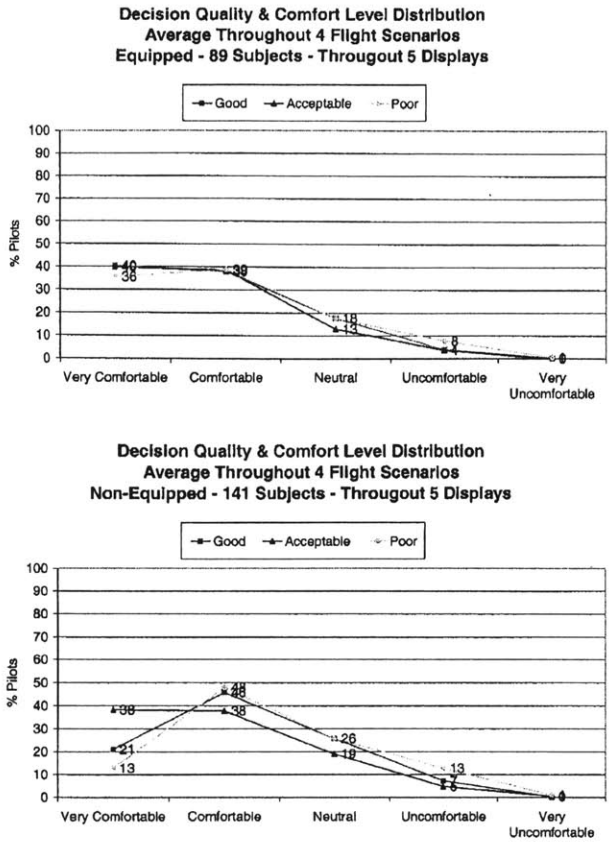


Fig. 9 Distribution of pilots' comfort level for three levels of decision quality.

For pilots of both types of operations, results show preference for graphical displays over text, and preference for three-dimensional displays (i.e., displays incorporating both horizontal and profile views) over two-dimensional displays. Also, for both types of flight operations preferences are indicated within the three-dimensional-display category for three levels of icing information over range enhancement.

The only significant difference between equipped and nonequipped pilots was that twice as many equipped pilots indicated preference for display B (three-dimensional, min range, three levels) over display E (three-dimensional, max range, three levels), whereas the preference is reversed for pilots of nonequipped operations (for which only 22% more pilots indicated preference for E over B).

Summary of Influence of Display Features

In the following the influence of the display features will be discussed in terms of the combined objective and subjective results just mentioned.

Influence of Graphical Information

The objective decision performance, the decision comfort level, and the subjective comparisons all indicated that graphical icing information is desirable.

Decisions made without the support of graphical information were, in all cases, inferior to decisions made with the graphical information. As shown in Fig. 8, for both equipped and nonequipped operations the largest percentage (over 50%) made poor decisions when using textual information only (53% of pilots in equipped operations and 56% of pilots in nonequipped operations). Also, the lowest percentage of pilots made good decisions based on textual information only: 35 and 24%, for equipped and nonequipped operations, respectively.

When provided with textual information only, fewer pilots rated their decisions as very comfortable and comfortable. Also, display A was by far the least preferred display of all.

Influence of Vertical Display

For both equipped and nonequipped groups a consistently smaller percentage of good decisions and larger percentage of poor decisions were observed with display D (two-dimensional, max range, three levels) than with display E (three-dimensional, max range, three levels). A vertical view was found to be valuable in identifying vertical maneuvers, which often corresponded to the most appropriate escape and avoidance maneuvers in the flight scenarios encountered.

The lack of vertical depiction in display D corresponded with more lateral deviations than vertical deviations in cases where both vertical and lateral maneuvers were available.

A consistently larger percentage of poor decisions was observed when the vertical display was not available (e.g., with displays D and A). The importance of the vertical display was also apparent in the subjective ratings. Lower decision comfort levels were reported with display D than with display E. Display D was the least preferred graphical display.

Influence of Range

The only significant effect of range on decision quality was observed in scenario 3, where the larger range of the most enhanced display, display E, provided visibility of possible severe icing exposure, which was not apparent in the shorter range display. Also, pilot decision comfort level was not significantly different with the shorter range display, display B, than with other displays, except from display A (text only).

Range and display perspective are thought to be confounded in the experiment, specifically for equipped pilots. Equipped pilots actually indicated preference for the shorter range display B over other displays. Display B was preferred by a factor of two over display E (three-dimensional, max range, three levels) and by much greater factors over other displays. Although the experiment did not directly investigate the percentage of pilots, which used airborne weather radar, based on their flight qualifications (i.e., with 72% of equipped pilots indicating that they are qualified as airline transport pilots), it is likely that most of equipped pilots operate with airborne radar, which have features similar to display B. The indicated preference of equipped pilots for display B (three-dimensional, min range, three levels), referred to as airborne icing severity system in the experiment, is thought to relate to a preference for aircraft-centered perspective.

Influence of Icing Severity Levels

The single-severity-level display, display C (three-dimensional, max range, one level), was found to support decision quality similar to with the use of most enhanced display, display E. This indicates that information on areas where icing is present, even without severity-level information, is valuable. Indicated decision comfort levels with either displays were similar. However, display C was the least preferred of the three-dimensional displays.

Conclusions

To investigate the potential benefits of remotely detecting icing conditions, an experimental evaluation of pilot decision making in icing conditions was conducted with display features representative of potential remote ice-sensing systems. The main observations of this experiment are summarized next:

1) Graphical horizontal depiction of remotely detected icing information was found to be very valuable in supporting good routing decisions and was found to be desired by the subjects.

2) Vertical depiction combined with horizontal depiction of icing conditions was found, overall, to support better decision making, as it supported the most appropriate selection of vertical and horizontal escape and avoidance maneuvers. Further research could investigate the influence of vertical depiction without horizontal depiction of icing conditions on pilot routing decisions.

3) Graphical information on multiple icing severity levels was not found to support significantly better decision quality than graphical information on icing presence, especially for non-icing-equipped operations. In conjunction with the hypothesis that the accurate

detection of expected severity of an icing encounter is significantly more difficult than simply identifying the spatial location where icing can occur, this experimental result has significant implications for the remote ice sensing and forecasting efforts. The reason why identifying the spatial location where icing can occur and can be more easily detected is that it is often easier to identify the areas where icing conditions are not present based on either lack of visible moisture, which can often be detected by satellite remote-sensing, or regions where temperatures are above the freezing level.

Acknowledgments

This work was supported by the NASA John H. Glenn Research Center at Lewis Field under Grant NAG3-2178. The authors wish to acknowledge the collaboration of the numerous pilots who contributed to this work by sharing their experience through the completion of the Web-based experiment. The authors would like to thank Amerson L. Hongjie and Mario Rodriguez for very valuable help in analyzing the data and helping to run the experiment. The authors wish to thank Andrew Reehorst of the NASA John H. Glenn Research Center at Lewis Field and Charles Ryerson of the U.S. Army Cold Regions Research and Engineering Laboratory for useful feedback in preparing this work.

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APPENDIX E – IMPLICATIONS OF CONTINGENCY PLANNING SUPPORT

Vigeant-Langlois, L., R.J. Hansman, 2003: Implications of contingency planning support for weather and icing information. FAA In-flight Icing/Ground De-icing International Conference & Exhibition, Palmer House Hilton, Chicago, IL, June 16-20, 2003

2003-01-2089

Implications of Contingency Planning Support for Weather and Icing Information

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ABSTRACT

A human-centered systems analysis was applied to the adverse aircraft weather encounter problem in order to identify desirable functions of weather and icing information. The importance of contingency planning was identified as emerging from a system safety design methodology as well as from results of other aviation decision-making studies. The relationship between contingency planning support and information on regions clear of adverse weather was investigated in a scenario-based analysis. A rapid prototype example of the key elements in the depiction of icing conditions was developed in a case study, and the implications for the components of the icing information system were articulated.

INTRODUCTION

Icing remains one of the leading causes of aviation accidents. Icing information plays a paramount role in mitigating the safety impact of adverse weather by helping air transportation decision-makers avoid icing conditions beyond the capabilities of their aircraft. Several efforts target critical research and development needs in relation to the icing information system, including NASA's Aviation Weather Information program, the FAA's Aviation Weather Research Program and the Alliance Icing Research Study (Stough and Martzaklis, 2002; Kulesa *et al.*, 2002; Cober *et al.*, 2002). In order to continue developing the technology that will best support the needs of the key aviation decision-makers, it is important to ensure that their needs are understood.

A human-centered systems approach, that considers the function of the human as a part of a greater air transportation system is applied to the icing avoidance problem. In this approach, icing is analyzed under an adverse weather abstraction that draws insightful parallels with other adverse weather phenomena such as convective weather and non-convective turbulence. This abstraction is presented in the next section.

The next step involves the presentation of a human-centered systems approach applied to the adverse aircraft-weather avoidance problem. A model of pilots' weather-related decision-making is developed and articulates the role of contingency planning.

Building on these results, the subsequent section tackles the investigation of contingency planning support as a hazard mitigation strategy and its relationship to the presentation of information on *clear weather* regions. The implications for adverse weather information in general, as well as for icing in particular, are explored in the last part of this paper.

ABSTRACTION OF THE ADVERSE AIRCRAFT-WEATHER ENCOUNTER SITUATION DYNAMICS

Icing and other adverse weather phenomena occur in some instances with significant intensity that it is desirable for aircraft to avoid them. Of course, not all aircraft shall avoid the same intensity level of adverse weather conditions. In the case of icing, the user segmentation is primarily based on the certification level of aircraft, although other factors such as ice protection equipment, excess engine thrust, aircraft ceiling and type of operation (e.g., Part 121 versus Part 135 and Part 91) also matter.

From an operational perspective, the task of avoiding icing is similar to other weather avoidance tasks involving adverse convective weather and clear air turbulence. In these three tasks, the information available to decision-makers and the avoidance-related mitigation strategies have common attributes. In order to provide solutions for enhancing icing information in the operational context, it is hence desired to understand the differences and similarities across adverse aircraft-weather encounter problems.

An abstraction of the adverse aircraft-weather encounter problem is built and shown in Figure 1. As illustrated in the figure, aircraft transit along trajectories in an

environment where co-exists an aviation impact field (e.g., icing field). Adverse weather regions (e.g., regions of icing conditions) and clear weather regions (e.g., regions of ice free conditions) can be identified based on the values of aviation impact variables distributed in space and varying over time, that characterize the aviation impact field.

Generally, a nominal four-dimensional (4-D) aircraft trajectory, which is an aircraft route specified in space and time as the nominal route of flight operations, can be identified. For example, a flight route filed on a flight plan or entered in an aircraft flight management system would constitute a nominal 4-D aircraft trajectory. In addition, alternate 4-D aircraft trajectories, which are different from the nominal aircraft trajectory and which may be used when it is desired to deviate from the nominal aircraft trajectory, can also be defined. There is in theory an infinite number of available alternate aircraft trajectories, but some of them may actually be articulated in flight operations (e.g., route to alternate airport; alternate Standard Instrument Departure Procedure; alternate standard cruising altitudes).

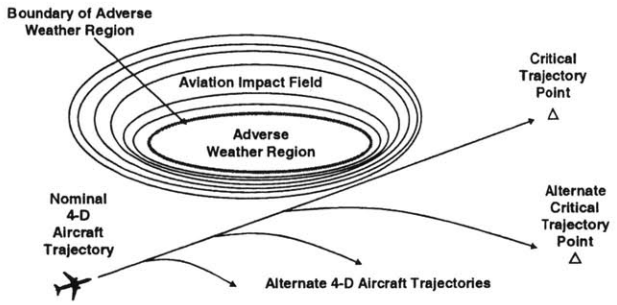

Figure 1: Key elements of the aircraft-weather encounter problem

Finally, critical trajectory points are defined as points in three-dimensional space where a nominal and several (at least partially) planned alternate 4-D aircraft trajectories intersect (e.g., origin and destination airports; airport corner post). Alternate critical trajectory points are also defined as critical trajectory points of alternate 4-D aircraft trajectories (e.g., alternate airport filed on a flight plan under Instrument Flight Rules (IFR)).

HUMAN-CENTERED SYSTEMS ANALYSIS

Human operators are at the center of tasks that involve keeping aircraft from flying into adverse weather conditions. A human-centered systems approach, integrating a systems engineering methodology and human factors considerations in the development of information systems, is applied to analyze the adverse aircraft-weather encounter problem. The approach considers the human as a functional component of the closed loop information and operational system.

An analysis of how the human operator fits in th operational environment of weather-related tasks wa conducted. The analysis builds on previous work relate to hazard alerting in aviation operations that applie mostly to terrain and traffic avoidance (Kuchar ar Hansman, 1995). A model of the information flow in th closed loop feedback process involving a pilot and th adverse aircraft-weather encounter *situation dynamics* presented in Figure 2. This model was developed abstract the current paradigm of the aviation weath system. It is based on a detailed survey of the curre aviation weather information sources as well as on a analysis of general and commercial aviation flig operations conducted through focused interviews ar surveys with pilots (Vigeant-Langlois and Hansma 2000). Essentially, the model includes four elements:

1. Components of the adverse aircraft-weather encounter *situation dynamics* including the adverse weather region and the aircraft;
2. The pilot;
3. The weather information system;
4. The aircraft state information and flight managemer system.

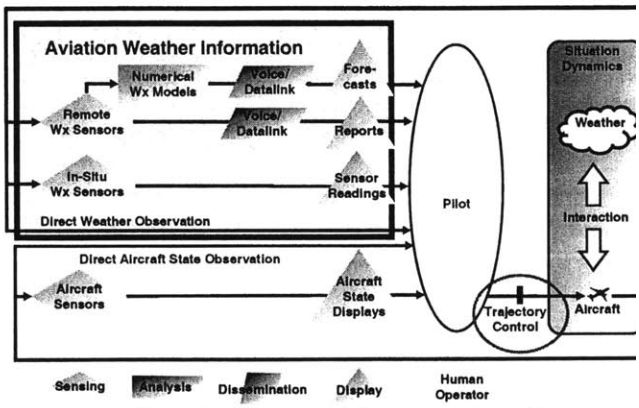

Figure 2: Model of information flow in aircraft-pilot feedback control loop in flight operations

Four important points emerge from the analysis and a mentioned below.

- The information available to the pilot about th situation dynamics is obtained via separa information feedback loops involving the weather ai the aircraft.
- The weather information available to the decisio maker comes from a variety of sources ai dissemination paths, as shown in Figure 2.
- The aircraft state and multi-source weath information is integrated by the decision-maker order to interact with the *situation dynamics*.
- The principal way for the human operator to cont the situation dynamics is via the control of the aircr trajectory, as highlighted in Figure 2.

Building on the model of information flow presented Figure 2 and in accordance with traditional methods

describe cognitive information processing, a model of pilots' weather-related decision-making was adapted from Endsley (1995) and Davison *et al.* (2003) and is shown in Figure 3. Herein, the internal representation includes a typical linear sequence of information-processing steps that progresses from perception to decision-making to action.

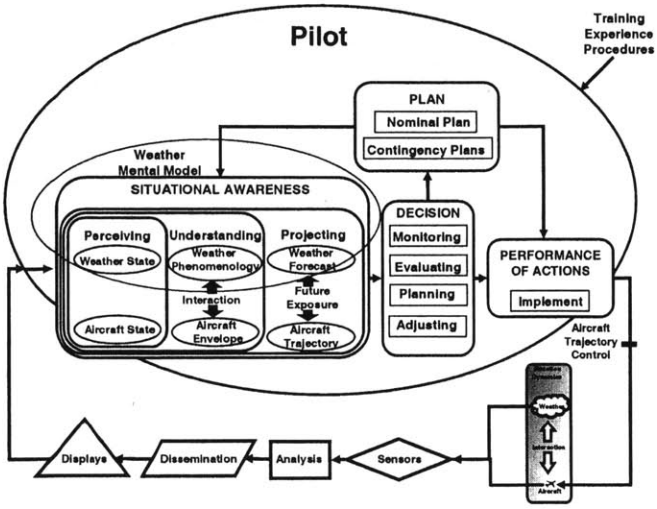

Figure 3: Model of information processing in weather decision process

An internal representation of the *situation dynamics* that serves to build the pilot's situation awareness construct is represented. The situational awareness component articulates the three levels of situational awareness mentioned by Endsley (perception, comprehension and projection) as functions of the aircraft and weather elements. A trajectory-based approach to weather information emerging from this model has been investigated in previous work (Vigeant-Langlois and Hansman, 2002).

It is hypothesized that a mental model of the weather is generated in the mind of the decision-maker based on weather information. This mental model is influenced by weather related training, experience and potentially procedures and interacts with the user's situational awareness, as shown in Figure 3. In addition to the traditional components, a plan construct is also included to articulate the influence of the formulation of intentions on situational awareness and on the performance of actions.

The influence of contingency plans on other decision constructs is also shown in Figure 3. The next section motivates and defines contingency planning support in the context of weather-related decision-making.

CONTINGENCY PLANNING SUPPORT

MOTIVATION

Weather-related contingency planning support appears to be a key solution in building safety into the air transportation system. Indeed, building on Leveson's methodology for addressing safety in the design of complex systems (1995), several examples in the four types of hazard mitigation strategies identified by Leveson point to contingency planning support. As shown in Figure 4, actions such as supporting avoidance and escape tasks can serve as hazard control strategies in the adverse encounter of an aircraft with an icing region.

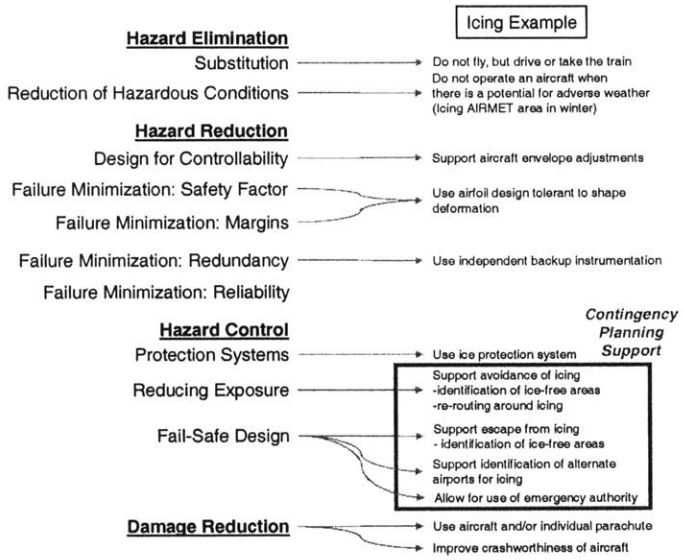

Figure 4: Design for safety methods applied to the icing problem

Other studies have identified to the value of contingency planning, such as in the option-based decision framework (shown in Figure 5) developed by Dershowitz and Hansman (1997).

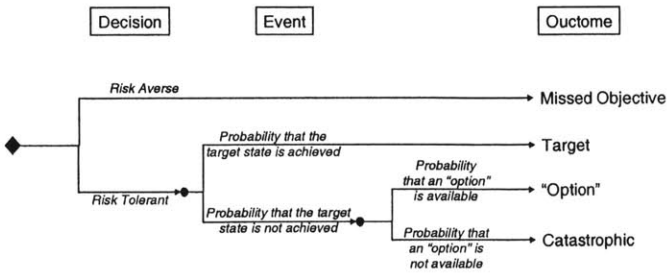

Figure 5: Option-based decision framework (based on Dershowitz and Hansman, 1997)

In this framework, an expected utility based approach to risk perception serves to point to the value of "options", or contingencies and their perceived probability. For example, the framework articulates that a rational

decision-maker would only select the risk tolerant branch if and only if he or she can identify readily available contingencies. Finally, Orasanu and Fischer (1997) also identified the value of contingency planning in the conclusions of a naturalistic decision study of the cockpit environment.

CONCEPT DEFINITION

The concept of contingency planning in the context of weather-related decision-making is introduced and discussed here. This discussion will serve as a basis to a contingency planning support analysis that will be discussed next.

First, a contingency is defined as an alternate course of action. For example, among the weather-related tasks conducted by pilots, the tasks consisting of *tactical avoidance* and *escaping* from adverse weather conditions constitute contingencies.

A contingency plan is defined as the formulation of an alternate course of action with some lead time. For example, selecting an alternate airport to the destination airport because of weather forecast constitutes a contingency plan. Weather information can help support the formulation of a contingency plan, by providing information that supports the identification of *alternate critical trajectory points* or *alternate 4-D aircraft trajectory* segments on the basis of adverse weather predictions.

It is observed that in aviation decision-making, a contingency may be formulated in situations involving decisions under uncertainty and high stakes. Its use may be triggered by the identification of current or projected undesirable conditions. The basis for assessing the undesirability of the conditions may relate to one or multiple goals founded on safety, legality, company or organizational policy, liability, comfort, training and public perception.

Moreover, contingency planning support involves information, training and/or procedures that help decision-makers consider and evaluate alternative options to the nominally intended course of action. For example, information, training and procedures that helps in the identification of areas free of adverse weather conditions (referred to earlier as *clear weather* regions) and in the formulation of alternate trajectory options such as cruising altitudes, routes of flights and destination airports.

For example, regulations currently require contingency planning for operations under IFR in specified weather forecast conditions. Under these conditions, fuel requirements involve not only sufficient fuel to reach the destination airport but also fuel to reach an alternate airport and to fly for an additional 45 minutes. For aircraft other than helicopters, the specified weather forecast conditions for which an alternate airport is required are specified in Part 91.167 of the Federal Aviation Regulations to involve situations where weather forecast predict that for at least 1 hour before and for 1 hour after the estimated time of arrival, the ceiling will be lower than 2,000 feet above the airport elevation and the visibility will be less than 3 miles.

Contingency planning support may come with an associated cost. Providing information on the location of areas free of adverse weather conditions may require additional resources for the surveillance, analysis, dissemination and presentation to the users. Moreover, procedures requiring contingency planning may lead to an increase in operational cost (e.g., associated with additionally required fuel) as well as reduced readiness. A cost-benefit analysis would help identify the value of contingency planning support.

An additional risk in supporting contingency planning relates to a potential shift in user behavior toward increased risk tolerance. An assessment of the influence of contingency planning support on risk perception should be further researched.

RELEVANCE OF *CLEAR WEATHER* REGION INFORMATION

Contingency planning support in the adverse aircraft-weather avoidance problem is especially useful for planning under high uncertainty, such as in cases in which the aviation impact field is not well known. This could be due to the challenges in finding good surrogate adverse aviation impact variables in near real-time, such as in the case of icing. It could also be due to the challenges in predicting the state of reliable surrogate variables beyond some predictability horizon, such as in the case of convective weather predictions several hours in the future.

The relevance of supporting contingency planning through information on high-confidence *clear weather* regions was explored in a scenario-based analysis and is described below. Throughout that discussion, three regions are mentioned: an *adverse weather* region (depicted in magenta), a *clear weather* region (depicted in white), as well as a *possibly adverse weather* region (depicted in grey) complementary to the two other regions. In the icing case, the adverse weather region may be based on high-confidence icing information either generated from analyses (such as using the Current Icing Potential index) or based directly on icing remote sensing or pilot weather report (PIREP) information. The clear weather region may correspond to high-confidence ice-free areas, based on regions of temperatures above freezing, low relative humidity and/or other relevant surrogate parameters. The possibly adverse weather region may be obtained by default from generating information about the two other regions.

Consider first a scenario in which only information on the *adverse weather* region is provided. In this scenario, information about a *clear weather* region is also provided by default. A rational decision-maker who has trust in the information would elect a trajectory around the adverse weather region, as depicted in Figure 6.

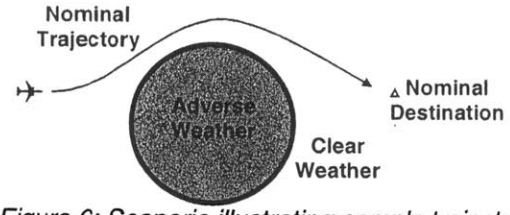

Figure 6: Scenario illustrating sample trajectory selection based on adverse weather information

Consider now that information is also provided on a *possibly adverse weather* region, but that its uncertainty level is unknown. Moreover, the decision-maker is informed that the *possibly adverse weather* region is identified in complement to a *clear weather* region known with high confidence. Even if a decision-maker elects to penetrate the *possibly adverse weather* region, he or she may benefit from the assessment that he or she has a readily available exit option. This scenario is depicted in Figure 7.

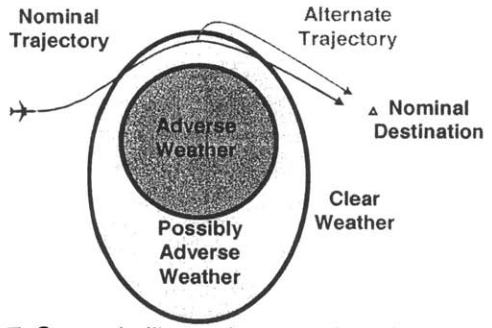

Figure 7: Scenario illustrating sample trajectory selection based on adverse weather and clear weather information

Consider now a third scenario in which the possibly adverse weather region affects the nominal destination. If the decision-maker elects to go, he or she may benefit from the information that an alternate destination is clear of adverse weather, as depicted in Figure 8.

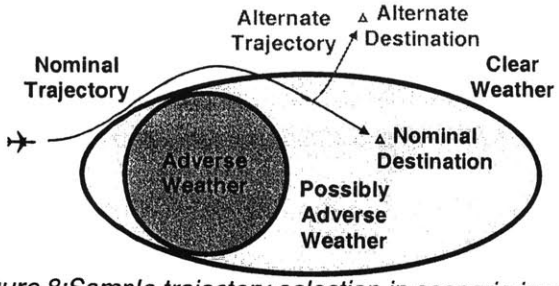

Figure 8:Sample trajectory selection in scenario in which the nominal destination is not in clear weather region

In the scenarios of Figure 7 and 8, a readily available contingency is only conceptually depicted as a relatively short distance to the *clear weather* region. In the icing case, it could for example involve an icing-free altitude 2,000 feet below.

These cases contrast with the scenario in which no contingency is readily available, such as depicted in Figure 9.

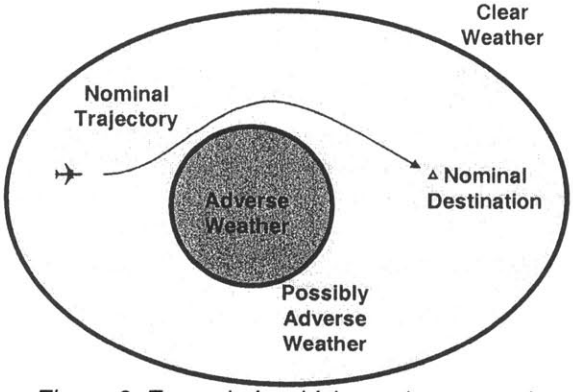

Figure 9: Example in which no alternate trajectory is available that readily reaches the clear weather region

In addition, the value of providing information on the *adverse weather* region is illustrated by comparing Figure 10 to Figure 6. Not knowing any better, a decision-maker may elect to proceed through an area that would otherwise be known to be adverse.

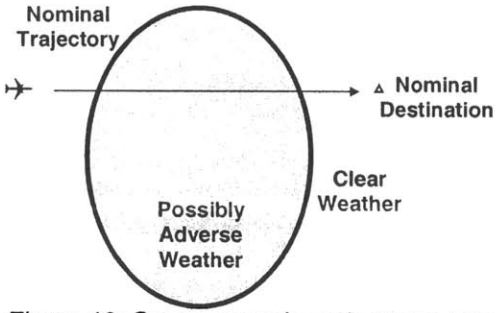

Figure 10: Same scenario as in Figure 6 but without information on the adverse weather region

In summary, it is hypothesized that information on *clear weather* regions may be used to support the identification of alternate trajectories; it may hence be desirable to provide it. It is not excluded that it may be desirable to provide more levels of adverse weather intensity, severity, or potential levels, such as is often used in adverse weather information. However this analysis shows the relationship between the provision of adverse weather information and its use by aviation decision-makers and points to the value of providing *clear weather* region information.

The scenario-based study mentioned above is not only applicable to the adverse weather avoidance problem, but also to other problems such as probabilistic studies of traffic and terrain avoidance. Yang and Kuchar (2000) for example used a similar approach to study traffic avoidance alerting criteria based on the availability of aircraft avoidance options. Also, Figures 6 through 10 provided only two-dimensional examples, but the method is expandable to larger dimensions such as four-dimensional space-time avoidance problems and more extensive state space approaches.

IMPLICATIONS FOR WEATHER AND ICING INFORMATION

The features of the depictions presented in the scenarios described in the previous section include depictions of high-confidence adverse weather areas and high-confidence clear weather areas. These features contrast with the information typically provided to pilots. In the case of icing conditions, icing AIRMETs are found to provide over-warning to pilots, based on their overly extensive nature when compared to the actual icing conditions encountered by pilots (Vigeant-Langlois and Hansman, 2000). In contrast, Current Icing Potential information provided on tools such as the Aviation Digital Data Service's Flight Path Tool feature ten levels of potential. The current analysis suggests that, once potential levels can be translated into high-confidence icing information, and high-confidence icing-free information, that these 10 levels could be translated into two levels for a given user.

With regard to convective weather, the problem is somewhat different. The confidence in the depiction of adverse convective weather based on surrogate parameters such as radar reflectivity factor is fairly high in near-real-time. However, it is found that the confidence in the forecast of adverse convective weather decreases with increasing forecast horizon, especially beyond a couple of hours (National Research Council of the National Academies, 2003). It is hypothesized that providing information with the two levels introduced here would be valuable, especially when forecast horizons extend beyond a couple of hours.

Building on the contingency planning support analysis presented above, a conceptual example of icing information representation was generated in a planar view and is presented in Figure 11. The representation displays regions where icing conditions are expected but where contingencies such as ice-free cruise levels are available (as depicted in green) and regions where these contingencies are not available (as depicted in magenta).

In this example, it was elected to identify the availability of cruise levels based on a comparison of ice-free region with Minimum Enroute Altitude (MEA) over a geographical area. Figure 12 illustrates a profile view the icing conditions along V270 between Boston (KBO and Elmira (KELM) airports for March 20, 2003 at 0900 As shown on Figure 12, there is at least one ice-fr cruise level available (6,000 feet). The depicti presented in Figure 12 was generated based on Curre Icing Potential information available through the Aviati Digital Data Service Flight Path Tool (c http://adds.aviationweather.noaa.gov) along victor airw V270 at 0900Z on March 20, 2003. High-confidence ici regions were determined based on 75% Current Ici Potential (CIP) or greater and high-confidence ice-fr regions were determined based on 5% or less of CI Possible icing areas were determined in complement the icing and ice-free regions. The CIP depiction bas on the Flight Path Tool for the same route and date provided in Figure 14 in the Appendix.

The depiction of MEA's on Figure 12 is based on da about victor airway V270 on Low-Altitude En-rou Charts (Air Chart Systems, 2002). Further analysis wou be recommended in order to determine the applicabil of MEA's off victor airways versus other altitudes such Off Route Obstruction Clearance Altitudes (OROC provided on US IFR Enroute Low Altitude Char Geographic Area Safe Altitudes (GASA) provided Canadian Enroute Low Altitude charts, Maximu Elevation Figures (MEF) provided on US sectior aeronautical charts, etc.

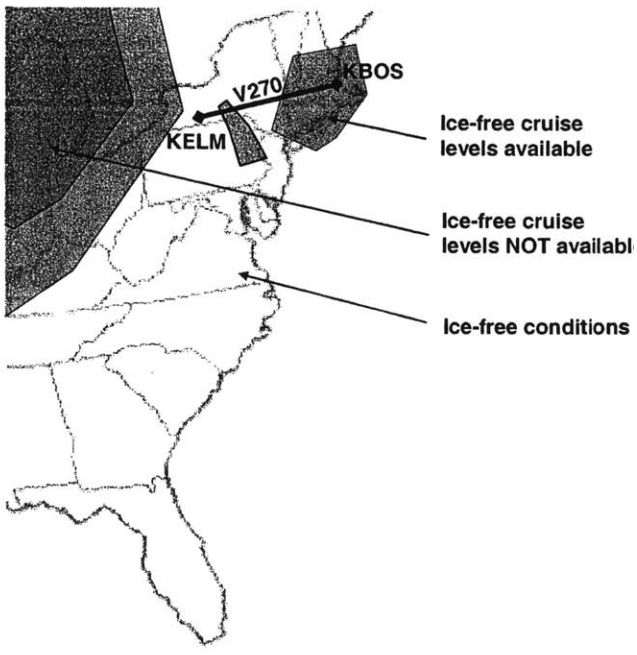

Figure 11: Conceptual example of planar view information articulating contingency planning options based on cruise levels

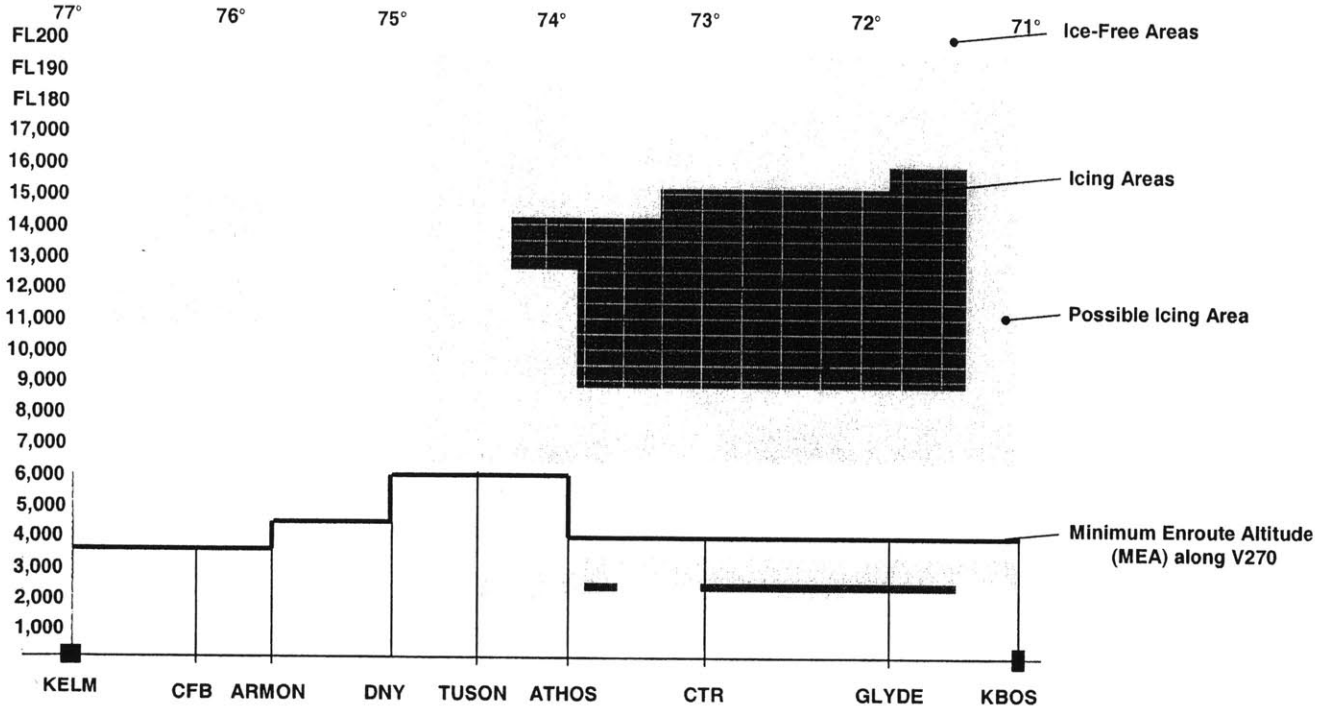

Figure 12: Example of icing region analysis along V270 on March 20, 2003 at 0900Z

In addition to having implications for the presentation of icing information, the analysis presented above also has implications for other elements of the icing information system, such as depicted in Figure 13. For example, information on the location of ice-free information would need to be generated on the basis of the surveillance of the ice-free region, as well as through modeling and dissemination.

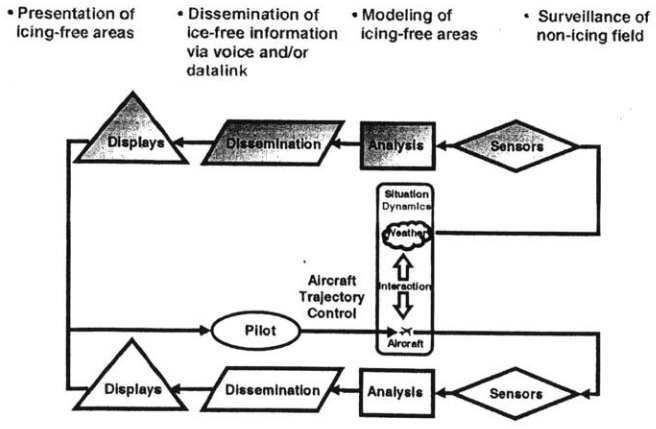

Figure 13:Examples of implications of contingency planning support for icing information system elements

CONCLUSIONS

An adverse aircraft-weather encounter problem abstraction was presented in this paper to provide insights to help understand and address the icing problem. Using this abstraction, a model of pilots' weather-related decision-making was built to articulate the role of contingency planning support. This result, combined with a system safety perspective applied to the adverse weather encounter problem, suggested that means to support weather-related contingency planning should be pursued.

A scenario-based analysis demonstrated the relationship between high-confidence *clear weather* information and the identification of contingency trajectories. The analysis pointed to the value of the information on *clear weather* regions, an important feature which is not currently emphasized in weather information. Building on these findings, the implications for icing information presentation in the vertical and planar views were explored using rapid prototyping methods. The implications for all elements of the icing information system were also articulated.

ACKNOWLEDGMENTS

This work was supported by the National Aeronautics and Space Administration Glenn Research Center under grant NAG3-2178. The authors wish to thank Captain A.H. Midkiff of American Airlines and Drs. Andrew Reehorst and Tom Bond of NASA Glenn Research Center.

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APPENDIX

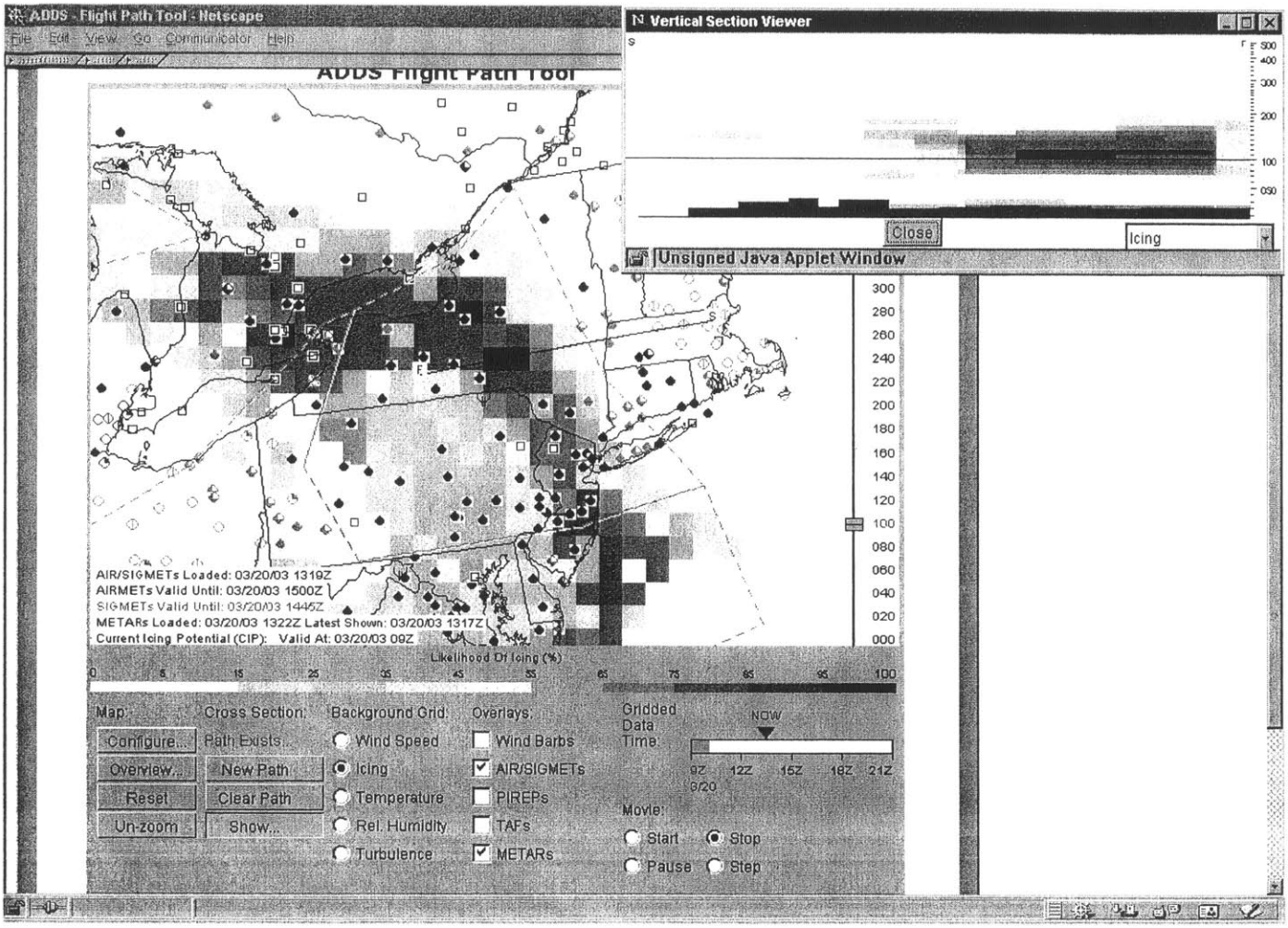


Figure 14: Planar and profile views of the Current Icing Potential along V270 on March 20, 2003 at 0900Z

APPENDIX F - VALIDATION OF MODELS OF ADVERSE AIRCRAFT-WEATHER ENCOUNTER

Objective

The objective of the study was to interview expert meteorologists and pilots to validate models of decision-making that were developed in the context of Chapter 3.

Protocol & Data Collection

Experts were either interviewed in person or over the phone with visual support from coloured slides. The protocol involved having experts review and provide comments for each decision process model and answer the following question: "Does the model make sense to you? Please answer according to a 3-point scale, as either:

- I agree with it
- I don't agree with it
- I generally agree but have recommendations for improvement, which are..."

Decision Model Design

Eight models of cognitive processes were presented, as listed below:

1. Aircraft-weather encounter abstraction
2. Information flow model
3. Model of pilots' weather-related functions and cognitive tasks
4. Model of pilots' cognitive processes
5. Temporal regimes of weather predictability: uncertainty growth with forecast horizon
6. Interaction between temporal regimes
7. Interaction between temporal regimes: matrix version
8. Illustration of four-dimensional intersection test

Focused Interview Material

The 10 slides presented below constituted the graphical material that was used during the focused interviews.

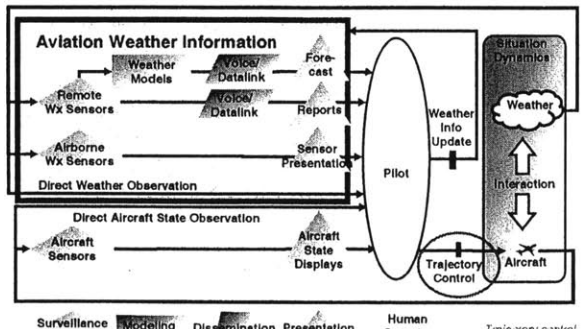
Introduction

- **High-Level Study Goal**
  - Guide the improvement of weather information systems
- **Focused Interview Objective**
  - Interview experts (meteorologists & pilots) to validate models of decision-making
- **Protocol**
  - Review and provide comments for each model, by answering the following question:
    - *Does the model make sense to you? Please answer according to a 3-point scale*
      - *I agree with it*
      - *I don't agree with it*
      - *I generally agree but I have recommendations for improvement, which are...*

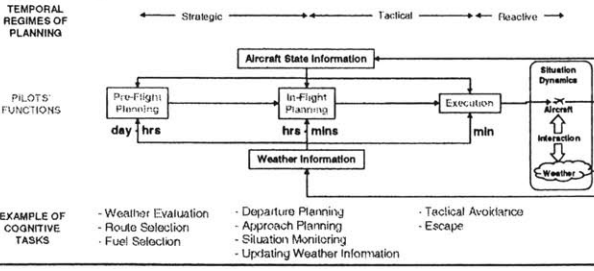
Subject Name	Meteorologist?	Pilot?
		Hours Certificates

	Agree	Disagree	Agree but with Comments
Slide 1			
Slide 2			
Slide 3			
Slide 4			
Slide 5			
Slide 6			
Slide 7			
Slide 8			

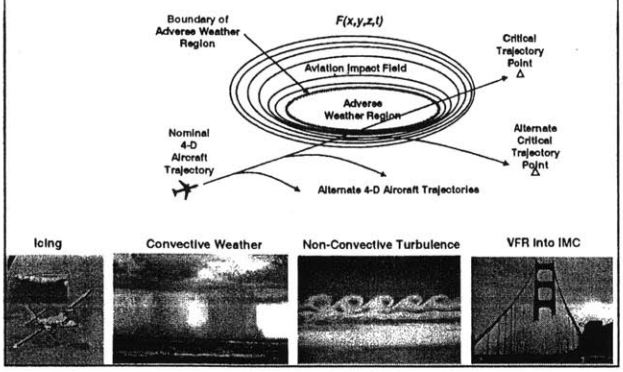
Information Flow Model 2



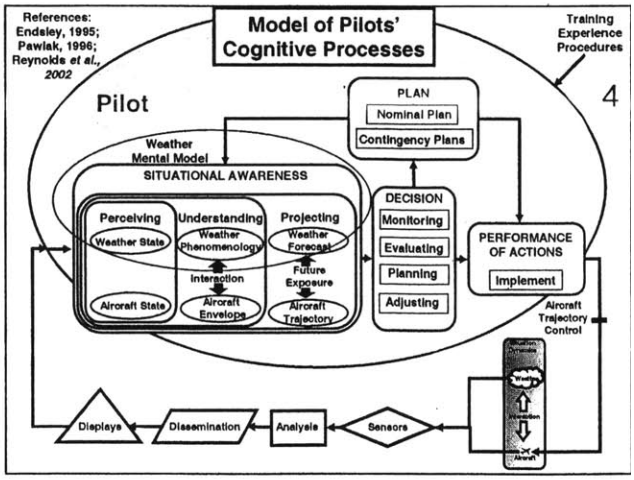
Model of Pilots' Weather-Related Functions and Cognitive Tasks 3



Aircraft-Weather Encounter Abstraction 1



Model of Pilots' Cognitive Processes 4



Temporal Regimes of Wx Predictability
Uncertainty Growth with Forecast Horizon 5

Time constants dependent on:
- Weather phenomena/variables (e.g., convective weather, turbulence, droplet size distribution, temperature)
- Phase of weather phenomena (e.g., storm initiation versus storm decay)

Weather representation based on observation over a time period where conditions do not significantly change

Weather representation based on deterministic forecast of "acceptable" accuracy

Weather representation at time in future beyond "predictability limit"

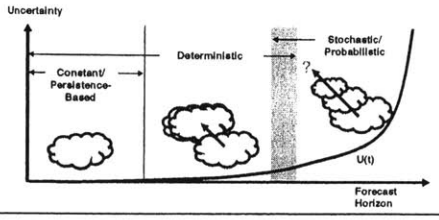
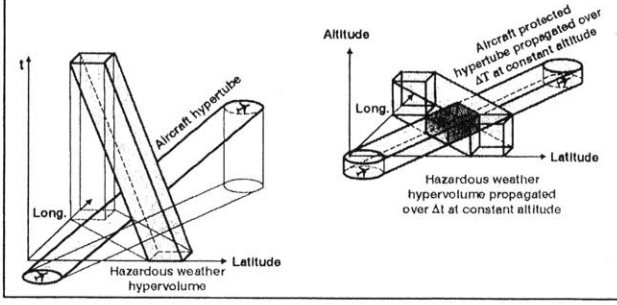
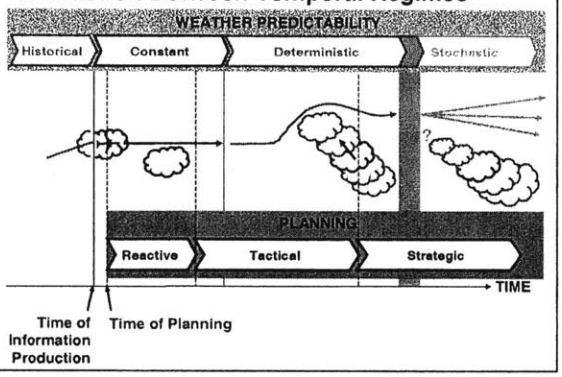


Illustration of 4-D Intersection Test 8

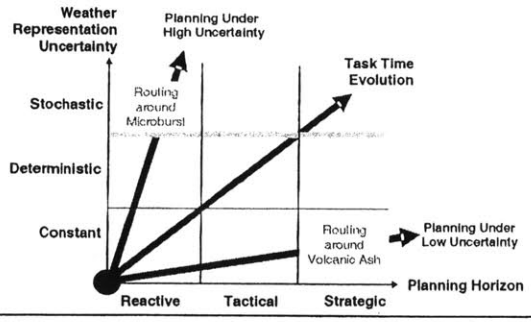
Assumptions
Deterministic regime
Hazardous weather boundaries identifiable
Uncertainty captured in *hypervolume* boundary buffers



Interaction Between Temporal Regimes 6



Interaction between Temporal Regimes 7



Subject Matter Experts

Following the initial model development, an external review of the models was conducted through interviews with ten independent aviation weather subject matter experts (SMEs). Each external reviewer was carefully selected for his or her demonstrated extensive expertise in either aviation meteorology, aviation or both. Eight of the SMEs selected were pilots, with experience ranging from general aviation to airline flying and including military flying as well as production and meteorological flight test. Eight of the SMEs were also nationally or internationally recognized aviation meteorology experts. Their expertise was either acquired through meteorological training or through extensive work in the field of aviation meteorology as part of national and international aviation weather programs. Three of the meteorological and aviation experts are also accomplished authors of books and articles widely published on the topic of aviation meteorology.

In more details, the SME reviewers included people with the following credentials:

- The manager of the National Center for Atmospheric Research's (NCAR's) Research Application Program;
- A meteorologist at NCAR and leader of one of the nationwide FAA Aviation Weather Research Program's Product Development Team;
- A radar and convective weather expert from the MIT Lincoln Laboratory and father of several key aviation weather decision support systems implemented by the FAA;
- An airline pilot with eight type ratings, test pilot for the FAA, meteorologist and author of books on severe weather flying;
- A former test pilot and manager of flight tests for NASA and Bombardier;
- A internationally renowned aviation weather consultant and former U.S. Navy pilot;
- A senior airline captain and the first woman to fly a Boeing 747;
- A human factors expert at NCAR, retired Navy pilot and leader of one of the nationwide FAA Aviation Weather Research Program's Product Development Team;
- An internationally renowned aviation weather writer and former airline pilot;
- A commercial pilot and flight instructor and author of over 650 magazine articles and a monthly column on aviation weather flying for the widely read Aircraft Owners and Pilots Association (AOPA) magazine.

Appendix Table A reviews the respective flight- and weather-related credentials of the ten SME reviewers.

Appendix Table H: Summary of flight- and weather-related credentials of the SME reviewers

SME Reviewer	Flying Experience	Flying Affiliation	Meteorologist	Meteorological Affiliation
1	Commercial & GA	-	Manager of RAP	NCAR
2	-	-	FAA PDT Leader, Wx PhD	NCAR, FAA
3	-	-	Convective Weather Expert	MIT LL
4	Environmental & Engineering Flight Test	FAA	Meteorologist & Author	Penn State
5	Engineering Flight Test	NASA, Bombardier	Icing Expert	NASA's Icing Branch
6	Environmental Flight Test & Military	US Navy, NCAR	Certified Meteorology Consultant & Wx PhD	NCAR, Consulting
7	Major Air Carrier	American Airlines	-	-
8	Commercial & Military	US Navy	FAA PDT Leader	NCAR, FAA PDT
9	Major Air Carrier	TWA	Author of Widely Read Aviation Weather Book	-
10	Flight Instruction	AOPA	Widely Read Author of Aviation Weather Articles	AOPA

Protocol and Results

Three of the ten SMEs were interviewed in person and the others were interviewed over the phone. All interviews were conducted with the support of colored graphical material, either on paper (for all three in-person interviews and two of the phone interviews) or in electronic format. For each model and representation, the SME reviewers were asked to rate their level of agreement on a three-point scale as either: 1) I agree with the model; 2) I disagree with the model; 3) I generally agree with the model but have comments for modification or improvement. The comments were collected and documented by the author during each interview. The most relevant comments were also incorporated in the progressively refined models and framework. A summary of the results of the focused interviews is presented in Appendix Table I.

Appendix Table I: Results of focused interviews on pilots' weather-related models

Model	Fig.	Title	Test Subject Answer		
			Agreed	Agreed with Comments	Did Not Agree
1	3-1	Closed-loop feedback process of pilot-aircraft-weather encounter	7	3	0
2	3-2	Model of aircraft-weather encounter	6	4	0
3	3-3	Model of information flow	6	4	0
4	3-4	Model of pilots' cognitive processes	5	5	0
5	3-5	Temporal representation of pilots' functions	9	1	0
6	3-8	Temporal representation of weather prediction uncertainty	3	7	0
7	3-11	Example of interaction between temporal representations	9	1	0
8	3-10	Illustration of interaction between temporal representations	9	1	0
9	3-12	Illustration of the effect of information ageing	10	0	0
10	4-xx	Illustration of four-dimensional intersection test	7	3	0

It was found that no SME reviewer disagreed with any of the model or representation. Most comments related to some details of the representations and models and served to progressively refine the models shown in Figures 3-1 through 3-12. A review of the comments made in relation to the models and representations is provided below and a summary is shown in Appendix Table J.

Appendix Table J: Notes taken during focused interview results (n=10)

	Model									
SME	1	2	3	4	5	6	7	8	9	10
1	ok	Ok	- diagnostic,nowcast? - include interaction with wx / info request	ok	ok	- constant/ persistence-based	ok	ok	ok	ok
2	ok	ok	ok	ok	ok	- issues with some terms: stochastic/not organized - variation with storm initiation vs. decay	ok	- like matrix, populate it	ok	ok
3	ok	ok	ok	ok	ok	- example of airborne radar vs. cst regime needs nuancing (see 2 pages)	ok	ok	ok	ok
4	ok	ok	-on-aircraft weather sensors - situation dynamics not obvious what it conveys	-situation dynamics makes sense there	ok	Ok	ok	ok	ok	In theory, not sure in practice
5	ok	ok	Ok	- include / discuss influence of experience, training, procedures	ok	Ok	ok	ok	ok	ok
6	- add direct observation - interaction awkward in generic sense (conv. Wx)	- Find better pix for IMC	- include link between aircraft sensors and wx models - clarify a/c vs. airborne sensors	ok	ok	- think of icing instead of DSD and T - include icing and wind examples in pix - add shrinking wx in r.h. column	- include other example s	ok	ok	- could include case with stochastic
7	- Add direct observation	- Add option to go around	- add PIREPs representation	- Crew resource management - 2-pilot vs. 1-pilot model	ok	- what about totally unforecast	ok	ok	ok	- Move around & label title
8	ok	ok	ok	ok	ok	Ok	ok	ok	ok	ok
9	ok	-pb with ATC constraint to trajectories MVFR hazaroud s VFR	ok	Surface analysis not teaching meteorology anymore/ depends on type of pilot	ok	- stochastic pb 30 min.	ok	ok	ok	ok
10	- include ATC and FSS	- include LIMC <500' vis. 1 nm.	Ok	- put EXPERIENCE in bold - emphasize judgment: knowledge, skill and judg.	Generally pilots good with tactica but not strategic/ small scale stuff gets to us	Give examples: stationary front; stochastic: onset of fzg rain Vs. passage of cold front predictable	ok	ok	ok	ok