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Implications of Contingency Planning Support for Weather and Icing Information

Laurence Vigeant-Langlois and R. John Hansman, Jr.
Massachusetts Institute of Technology, Cambridge, MA

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).

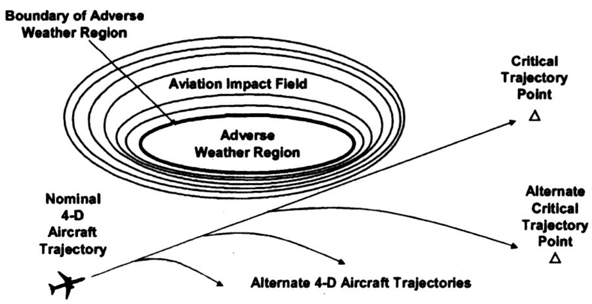

Figure 1: Key elements of the aircraft-weather encounter problem

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 the operational environment of weather-related tasks was conducted. The analysis builds on previous work related to hazard alerting in aviation operations that applied mostly to terrain and traffic avoidance (Kuchar and Hansman, 1995). A model of the information flow in the closed loop feedback process involving a pilot and the adverse aircraft-weather encounter *situation dynamics* is presented in Figure 2. This model was developed to abstract the current paradigm of the aviation weather system. It is based on a detailed survey of the current aviation weather information sources as well as on an analysis of general and commercial aviation flight operations conducted through focused interviews and surveys with pilots (Vigeant-Langlois and Hansman, 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 management system.

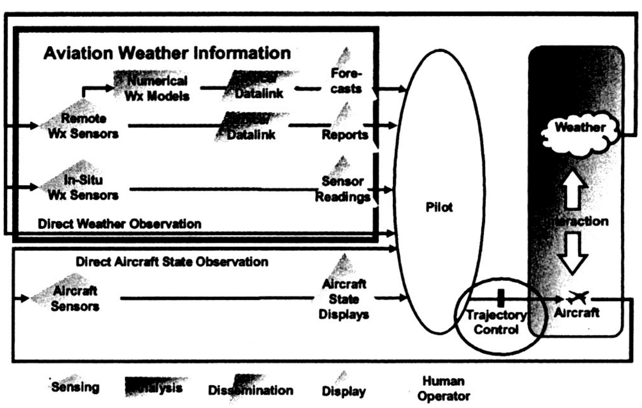

Figure 2: Model of information flow in aircraft-pilot feedback control loop in flight operations

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

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

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

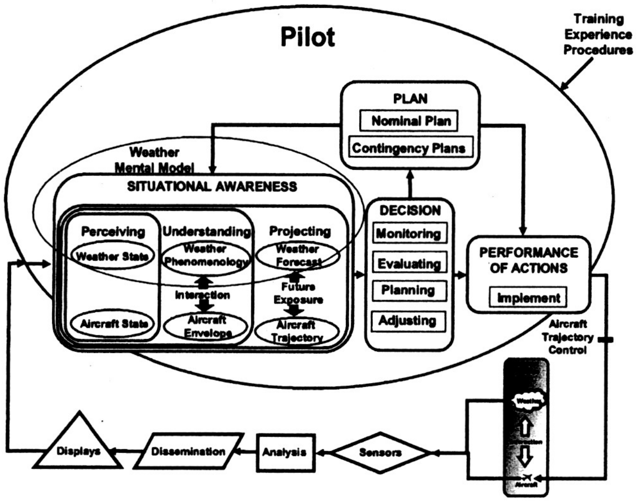

Figure 3: Model of information processing in weather decision process

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.

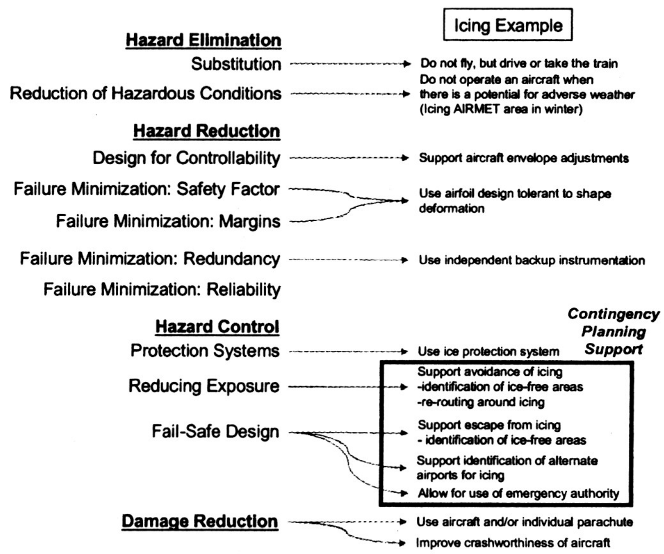

Figure 4: Design for safety methods applied to the icing problem

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).

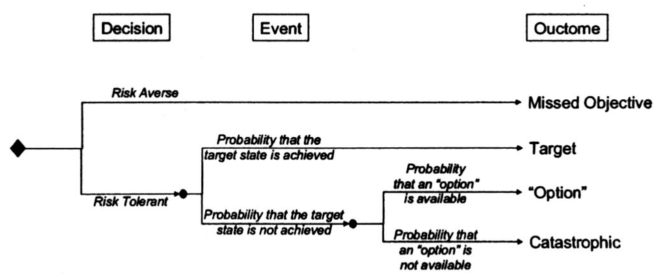

Figure 5: Option-based decision framework (based on Dershowitz and Hansman, 1997)

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.

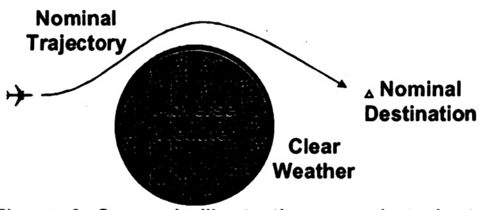

Figure 6: Scenario illustrating sample trajectory selection based on adverse weather information

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.

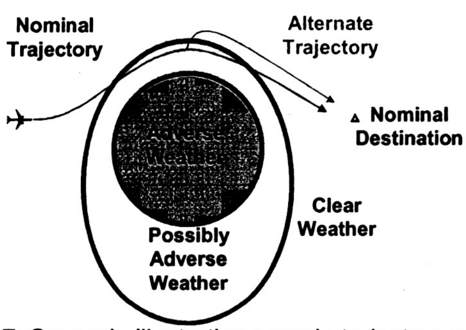

Figure 7: Scenario illustrating sample trajectory selection based on adverse weather and clear weather information

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.

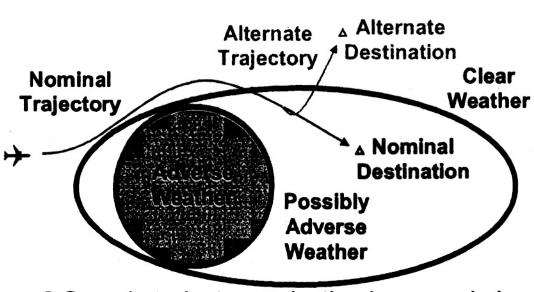

Figure 8:Sample trajectory selection in scenario in which the nominal destination is not in clear weather region

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.

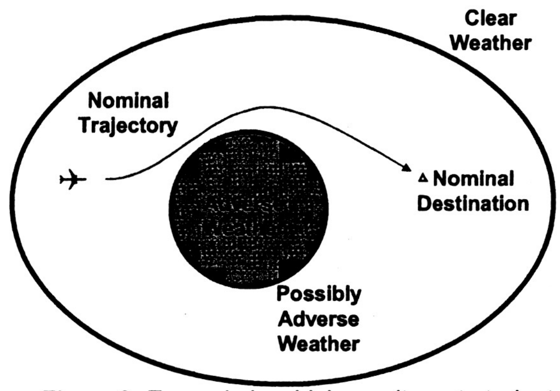

Figure 9: Example in which no alternate trajectory is available that readily reaches the clear weather region

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.

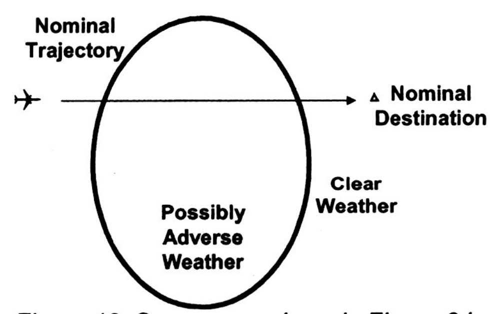

Figure 10: Same scenario as in Figure 6 but without information on the adverse weather region

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 of the icing conditions along V270 between Boston (KBOS) and Elmira (KELM) airports for March 20, 2003 at 0900Z. As shown on Figure 12, there is at least one ice-free cruise level available (6,000 feet). The depiction presented in Figure 12 was generated based on Current Icing Potential information available through the Aviation Digital Data Service Flight Path Tool (cf., http://adds.aviationweather.noaa.gov) along victor airway V270 at 0900Z on March 20, 2003. High-confidence icing regions were determined based on 75% Current Icing Potential (CIP) or greater and high-confidence ice-free regions were determined based on 5% or less of CIP. Possible icing areas were determined in complement to the icing and ice-free regions. The CIP depiction based on the Flight Path Tool for the same route and date is provided in Figure 14 in the Appendix.

The depiction of MEA's on Figure 12 is based on data about victor airway V270 on Low-Altitude En-route Charts (Air Chart Systems, 2002). Further analysis would be recommended in order to determine the applicability of MEA's off victor airways versus other altitudes such as Off Route Obstruction Clearance Altitudes (OROCA) provided on US IFR Enroute Low Altitude Charts, Geographic Area Safe Altitudes (GASA) provided on Canadian Enroute Low Altitude charts, Maximum Elevation Figures (MEF) provided on US sectional aeronautical charts, etc.

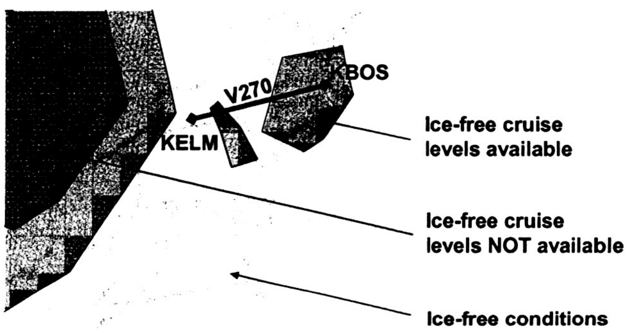

Figure 11: Conceptual example of planar view information articulating contingency planning options based on cruise levels

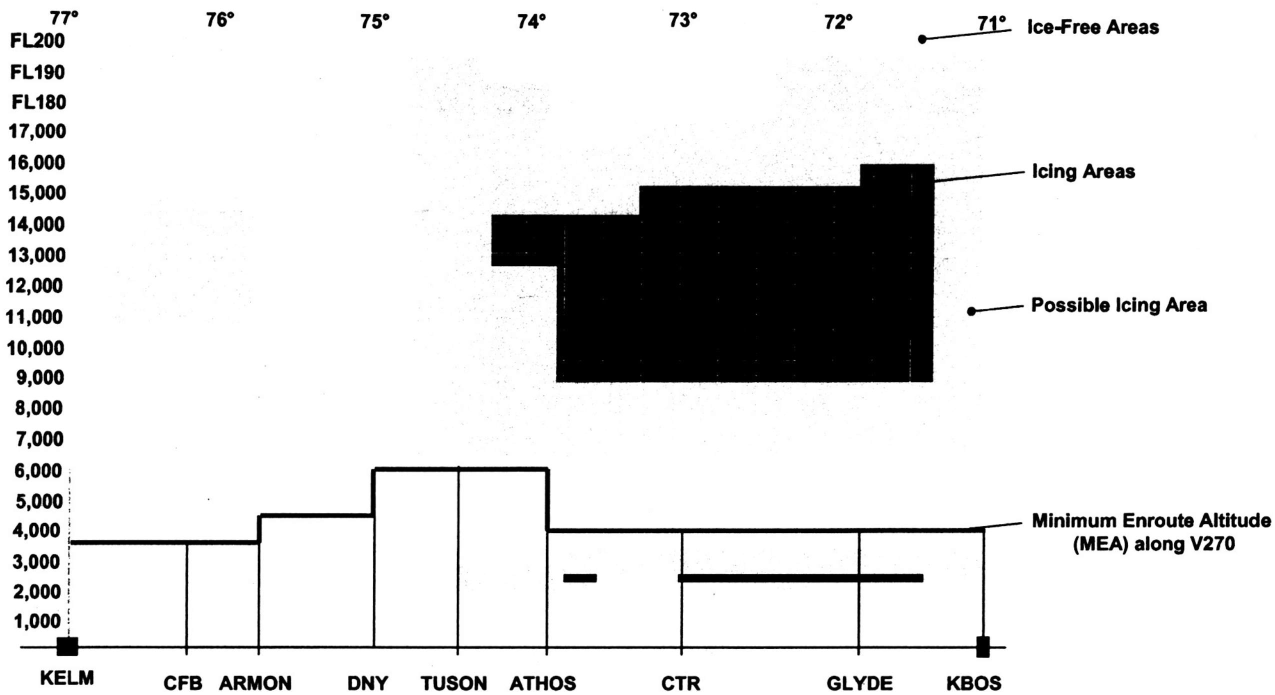

Figure 12: Example of icing region analysis along V270 on March 20, 2003 at 0900Z

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.

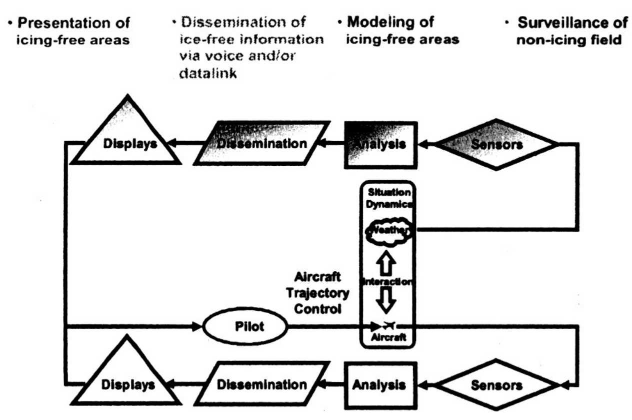

Figure 13:Examples of implications of contingency planning support for icing information system elements

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.

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CONTACT

Laurence Vigeant-Langlois is a doctoral candidate in the Department of Aeronautics & Astronautics at MIT. She is also a commercial pilot with experience flying for a commercial Part 135 carrier and a sailplane instructor. Before attending MIT, she completed a B. Eng. in Mechanical Engineering at McGill University. Her research interests focus on aviation weather, human factors and air transportation safety assurance. She can be reached at: 35-217 MIT, Cambridge, MA 02139, 617-253-3507;langlois@mit.edu.

R. John Hansman has been on the faculty of the Department of Aeronautics & Astronautics at MIT since 1982. He obtained his A.B. in Physics from Cornell University in 1976, his S.M. in Physics in 1980 and his Ph.D. in Physics, Meteorology, Aeronautics & Astronautics and Electrical Engineering from MIT in 1982. He is the Head of the Humans and Automation Division and is the Director of the MIT International Center for Air Transportation. His current research activities focus on advanced information systems and complex system issues in the operational domains of air traffic control, airline operations, aircraft cockpits, and automobiles. He can be reached at: 33-303 MIT, Cambridge, MA 02139, 671-253-2271; rjhans@mit.edu

APPENDIX

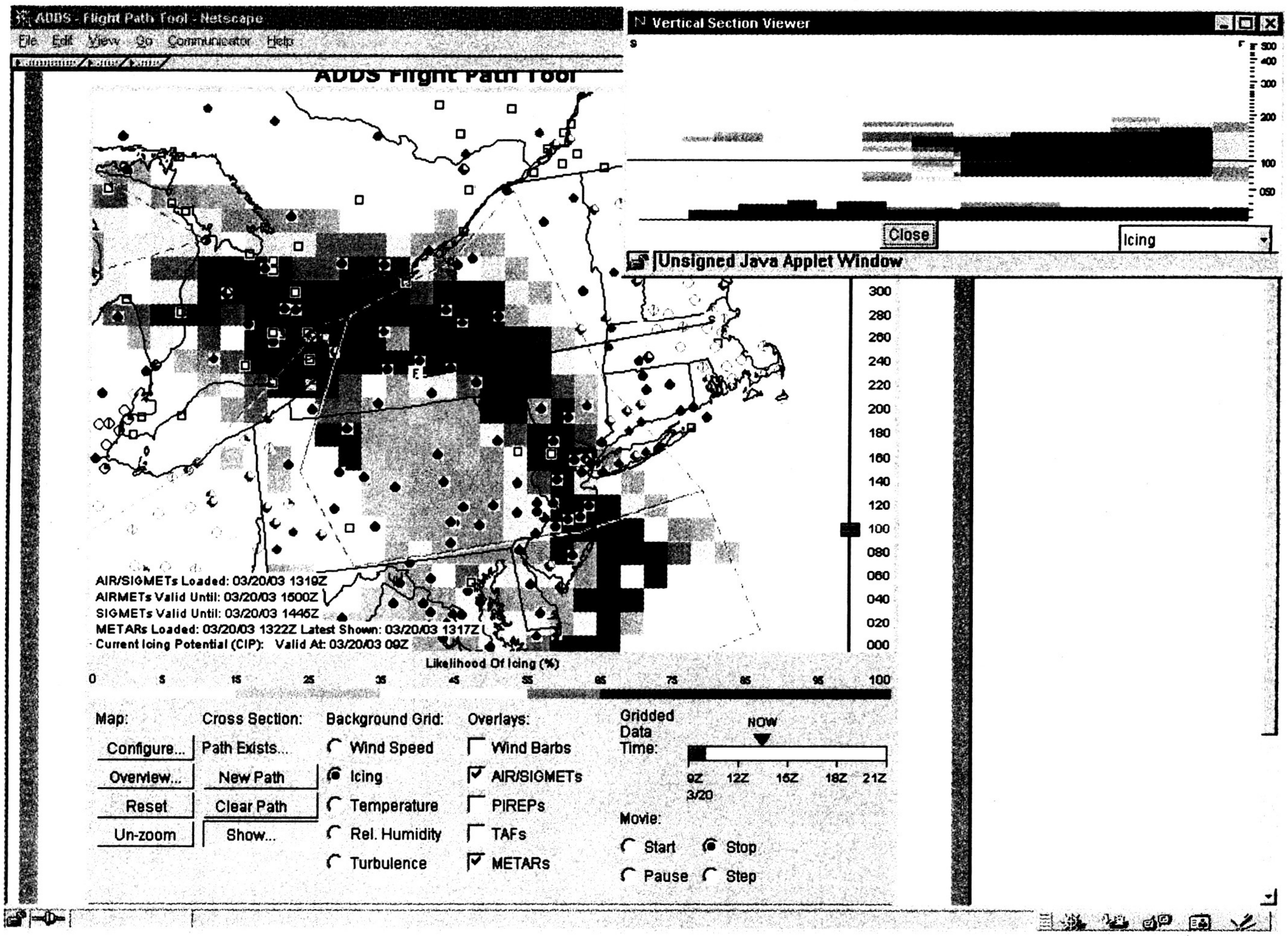

Figure 14: Planar and profile views of the Current Icing Potential along V270 on March 20, 2003 at 0900Z