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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

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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.

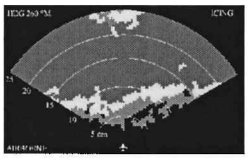
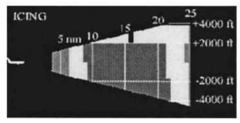
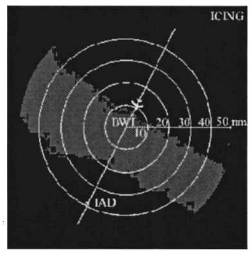
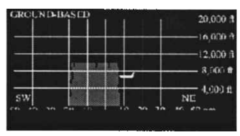
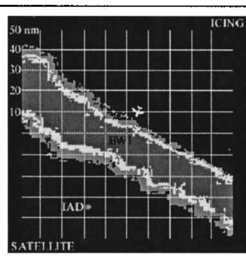
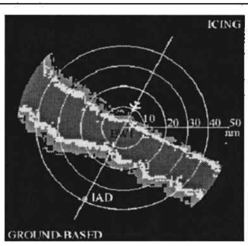
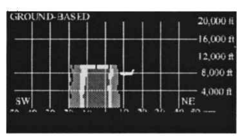
Display	Name in Web-Based Experiment	Graphical Representation	Sensor Range [nm]	Vertical View	Type of Icing Info.
Display A	Textual Information	×	×	×	×
Display B (3D, min range, 3 levels)	Airborne Icing Severity System		25 Min. Range		Icing Severity 3 Levels
Display C (3D, max range, 1 level)	Ground-based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

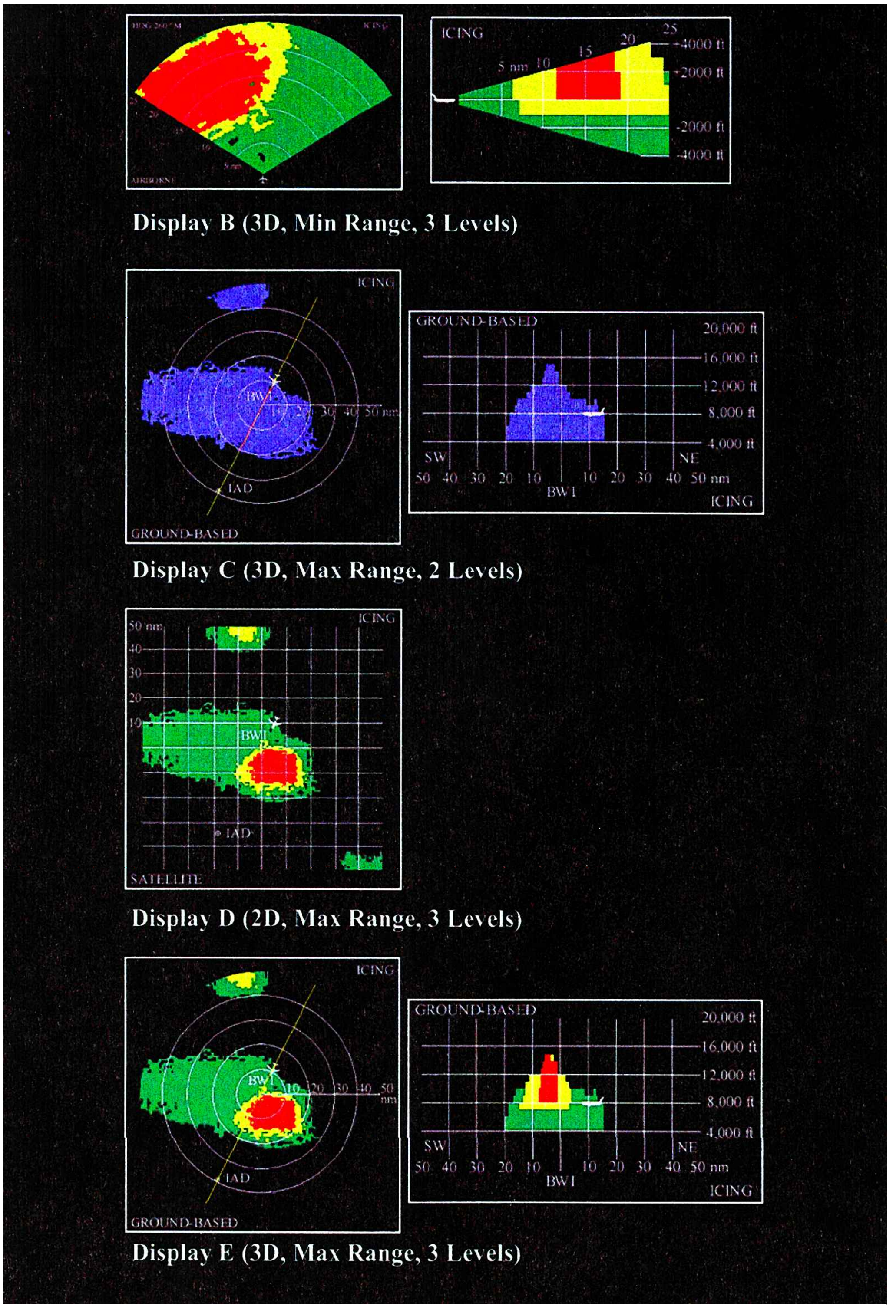


Fig. 2 Displays B–E depicting icing conditions in scenario 2 (black, no icing; green, trace; yellow, icing; red, severe icing; blue, icing—all severities).

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

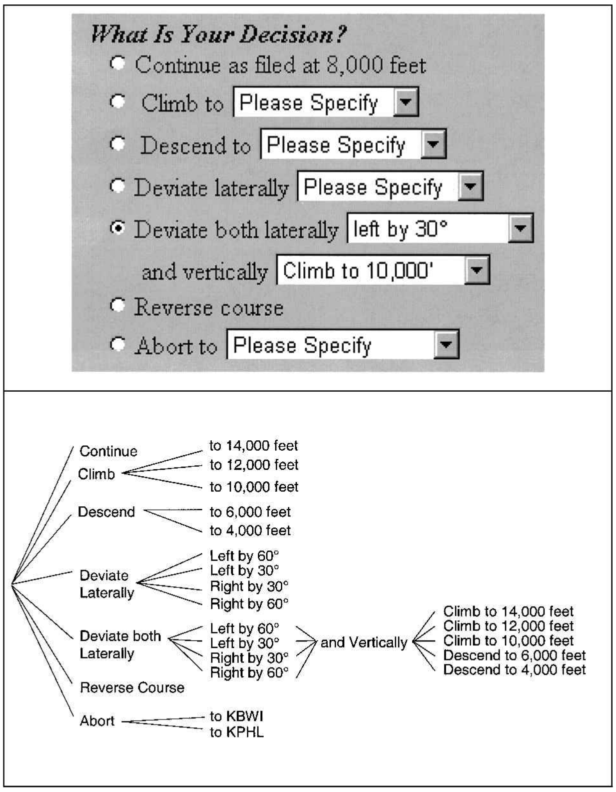


Fig. 3 Pilot selected routing decision (top) and routing decision tree (bottom).

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

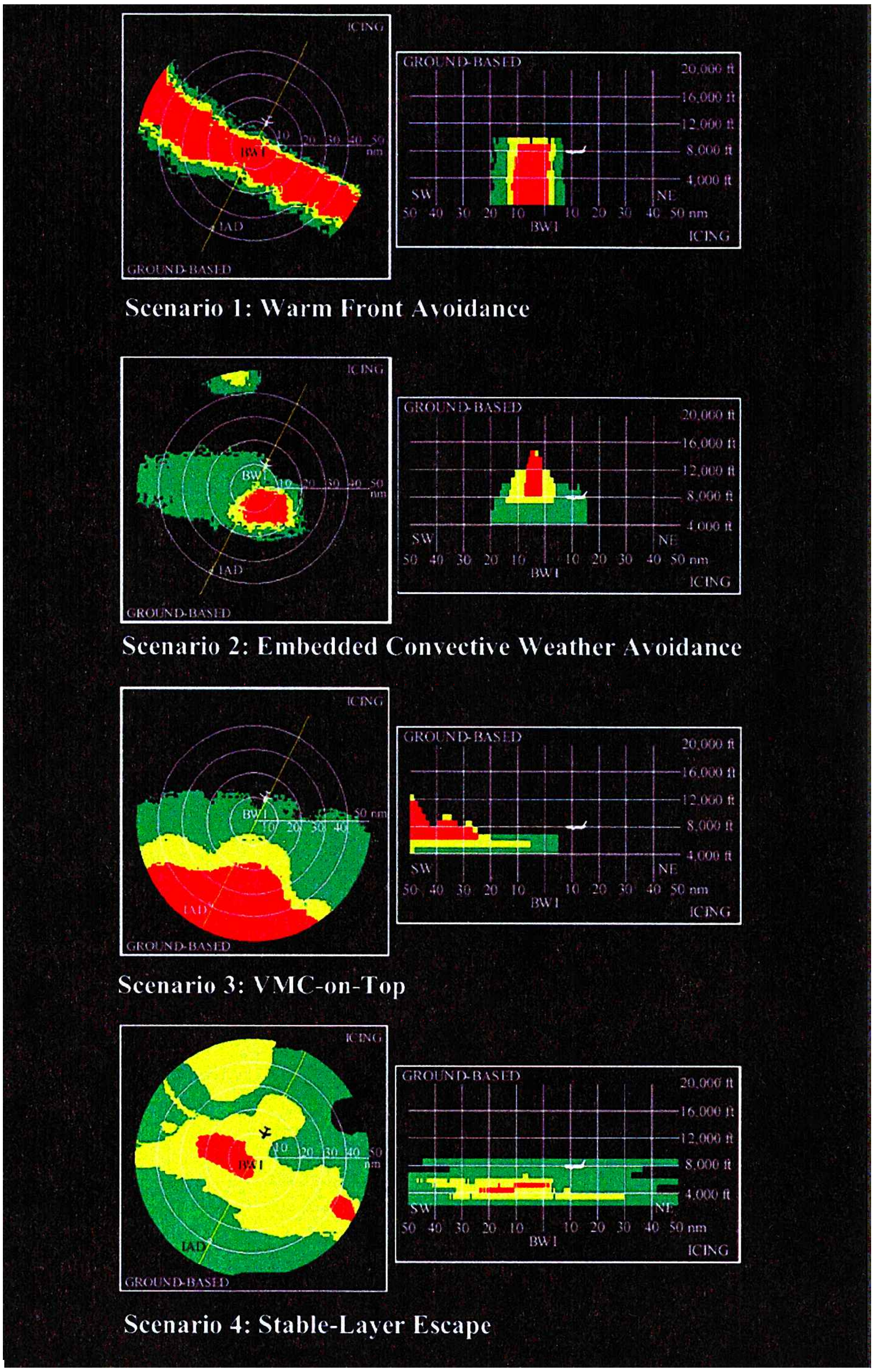


Fig. 4 Depiction of icing conditions in all four scenarios (black, no icing; green, trace; yellow, icing; red, severe icing).

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

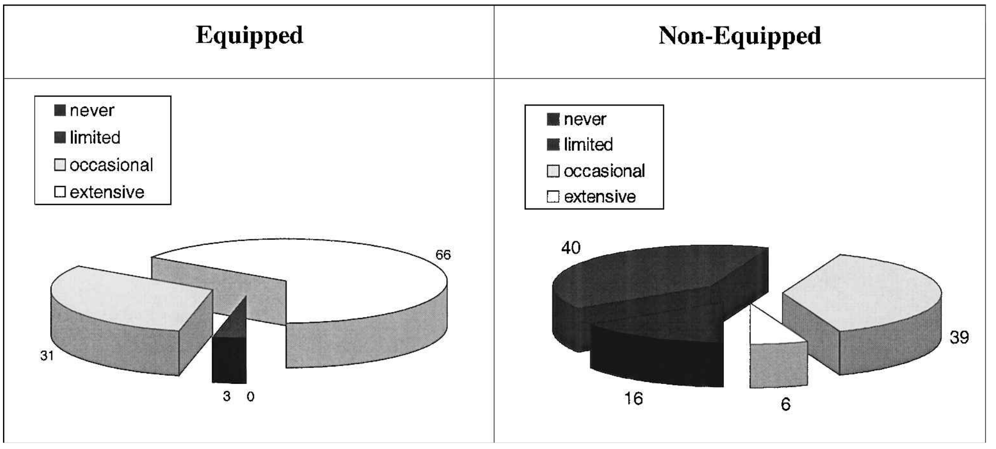


Fig. 5 Subjects' reported experience in icing conditions.

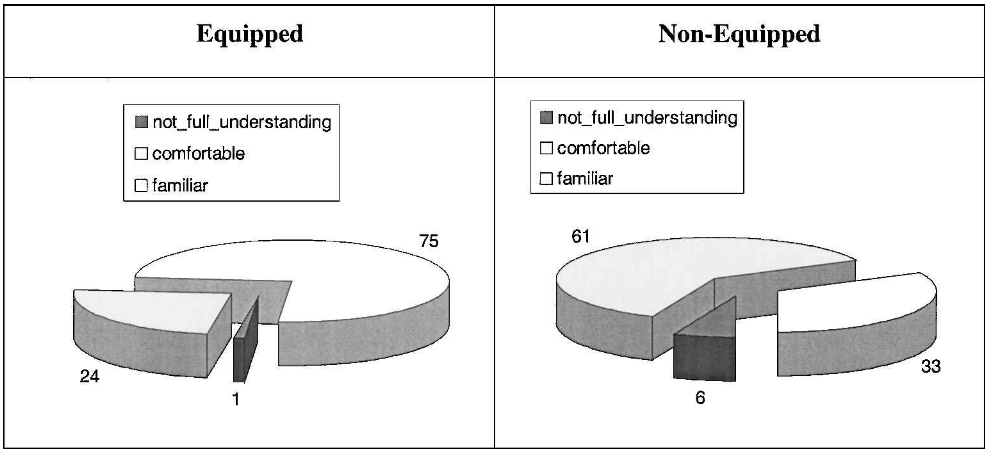


Fig. 6 Subjects' reported understanding of aircraft icing.

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-ranged 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.

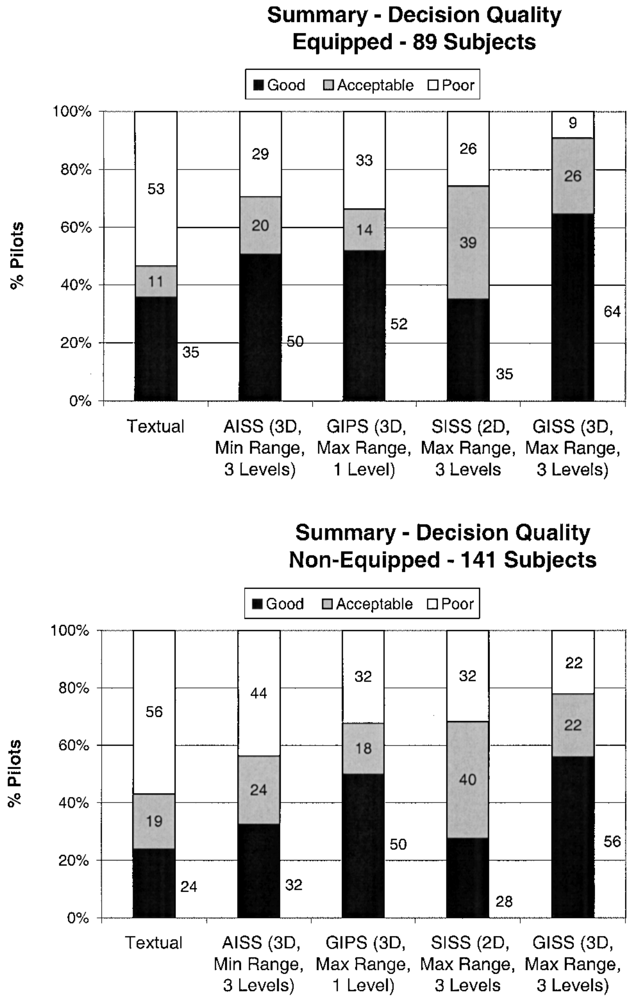


Fig. 7 Pilots' decision quality across all flight scenarios.

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.

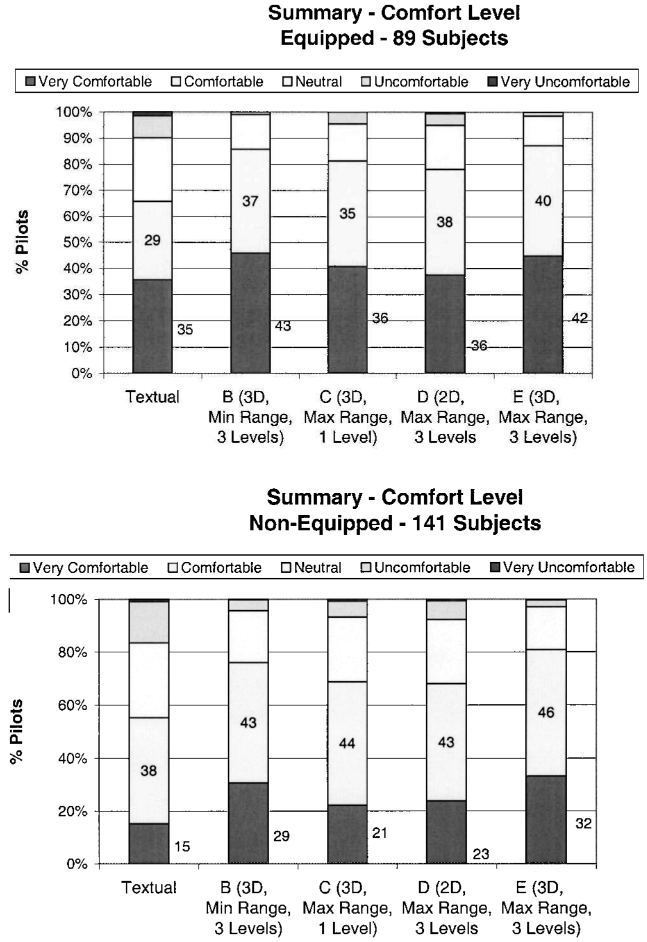


Fig. 8 Pilots' reported comfort levels across all flight scenarios.

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.

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).

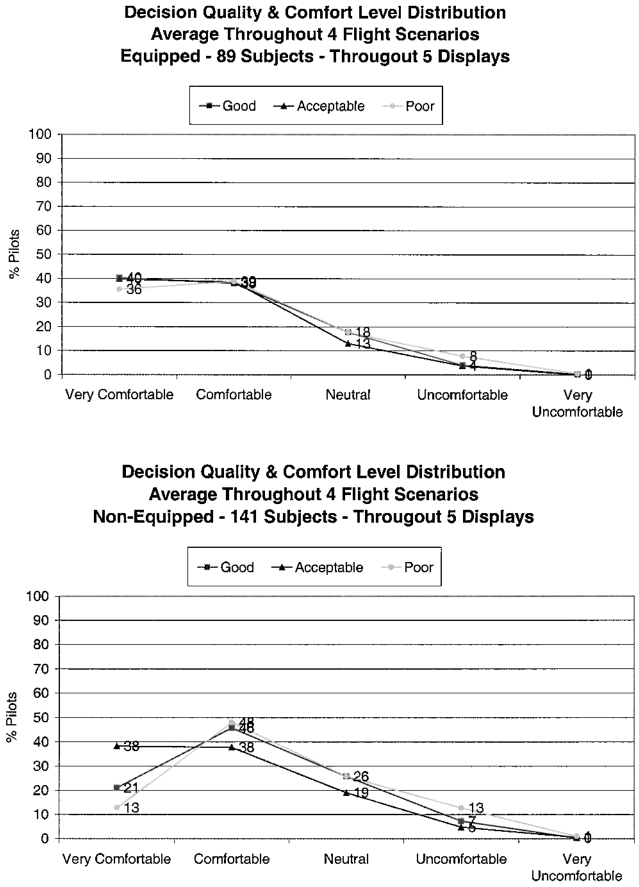


Fig. 9 Distribution of pilots' comfort level for three levels of decision quality.

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.

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