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Remote Sensing of In-Flight Icing Conditions: Operational, Meteorological, and Technological Considerations

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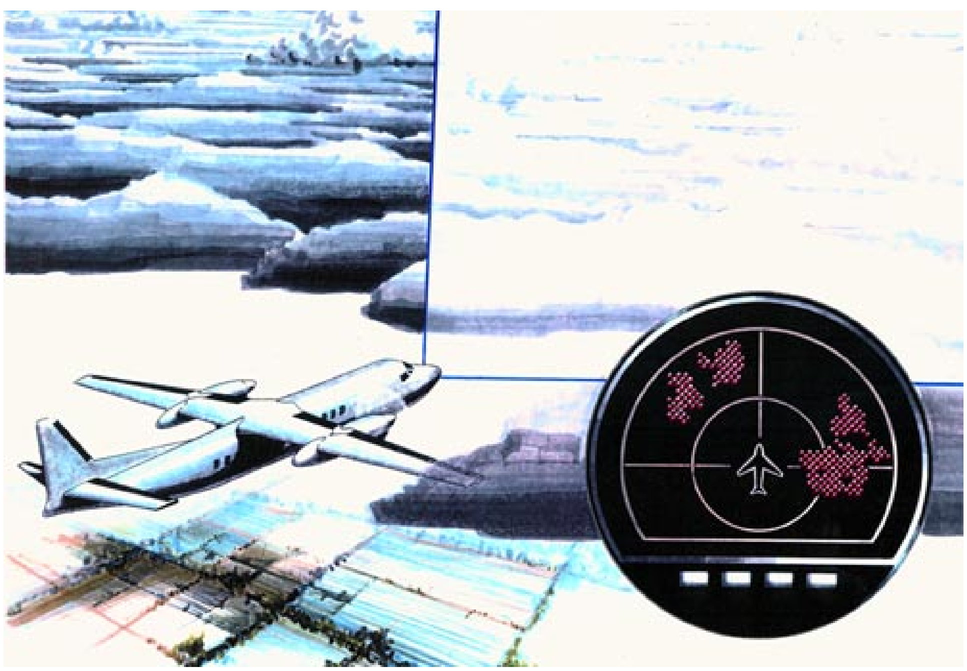

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Cover: Artist's rendering of possible cockpit display as aircraft enters regions of hazardous icing conditions. The display would be created from information gathered from either on-board remote sensors or ground-based sensors uplinking information to the aircraft.

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GLOSSARY

AGATE: Advanced General Aviation Technology Experiment.

ceilometer: An instrument that remotely measures the height of cloud base above ground level.

disdrometer: Instrument for measuring the sizes of raindrops.

exceedance conditions: Conditions outside of the envelope of conditions defined by FAR 25, Appendix C.

FAR 25, Appendix C: FAA Federal Aviation Regulation 25, Appendix C, defining the range of liquid water, drop size, temperature, and exposure conditions for which aircraft are certified for flight in icing.

Free Flight: FAA concept of autonomous aircraft flight, with aircraft–ground separation provided by onboard aircraft sensors rather than by air traffic control (ATC).

pireps: In-flight pilot reports of flying conditions, including icing.

prediction detection: Detection of icing condition remotely; remote-sensing system predictions that icing conditions are in the flight path.

range gate: The distance between consecutive radar measurements along a radial, typically about 100 to 500 m, and controlled by pulse duration.

reactive detection: Detection of icing conditions in situ; reaction of the in-situ instruments indicates that icing is occurring.

supercooled large drops (SLDs): Drops larger than typical cloud drops defined in FAR 25, Appendix C; typically drizzle drops ranging in diameter from 50 to 500 µm.

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1.0 EXECUTIVE SUMMARY

In-flight icing is a significant aviation risk despite improving icing forecasts and onboard ice protection systems. A remote-sensing system designed to detect icing conditions in the flight path could allow aircraft to avoid and exit hazardous conditions. Ground-based near airports or airborne, such systems would be most useful to low, slow-flying aircraft that frequently encounter icing, such as turboprops and helicopters. Development of an icing remote-sensing system requires consideration of the operational environment within which it is used, the meteorological environment it senses, and the technology available for sensing icing conditions.

Operationally, pilots need information in the cockpit for making risk-management decisions. Displays must evoke proper pilot decisions and provide clear, unambiguous warnings of severe conditions for avoidance. Human factors and cockpit and aircraft integration issues must be developed in addition to avoid-and-exit protocol and training. Dispatchers and meteorologists need integration of icing remote-sensing systems into the weather system infrastructure. Cost, maintenance, power, weight, and space are a concern of manufacturers, operators, and regulators, as is the evaluation of aircraft flight envelopes in icing conditions.

An icing remote-sensing system detects conditions conducive to icing, including cloud and precipitation liquid-water content, the drop-size spectrum, and temperature. An icing metric algorithm would convert these measurements into an estimate of icing potential for cockpit display. To develop specifications, the absolute magnitudes of cloud microphysical conditions and the spatial and temporal variability of icing weather conditions, must be understood at multiple scales. Icing cloud microphysics have been measured since the 1940s by NACA, NASA, the FAA, NCAR, and several universities. The absolute range of cloud liquid-water content in clouds of various genera is generally well known, but its vertical and horizontal distribution within clouds and cloud masses is not well understood. The cloud glaciation process is also imperfectly understood, as is the effect of mixed-phase conditions on aircraft icing and on cloud remote sensing. The shape of the drop-size spectrum is not well characterized in icing conditions, especially in supercooled large drops, and the median volume diameter does not often provide an adequate description of the drop-size spectrum, especially if the distribution is bimodal. Though it is generally known that static temperature changes more rapidly vertically than horizontally, there has been very little characterization of temperature distribution in icing conditions. The ability to detect temperature change ahead of an aircraft is critical, because the temperature within liquid water determines whether icing will occur. Characterization of icing conditions is expensive, typically requiring research aircraft. More reliable and less costly instrumentation is needed to replace first-generation optical probes, and to reduce cost, coordination is needed with other federal programs that make cloud microphysical measurements. Such cooperation has started between the Canadian Atmospheric Environment Service, Transport Canada, NASA, and the FAA.

The core of an icing avoidance system is the technology used to sense icing microphysical conditions. Radar and microwave radiometers are the most viable technologies. Ranging capability makes radar an attractive technology for detecting liquid water, drop size, and possibly temperature. Multiple-band radars, such as X and K_a bands to retrieve liquid-water content using differential attenuation techniques and X, K_a, and W bands to retrieve liquid water and drop size using neural nets, currently appear most viable. Information-

retrieval algorithms, noise, and Mie scattering present major radar technological challenges. Although radar can be used in a variety of orientations, scanning vertically from the ground or horizontally from the air, its size, weight, and power demands make ground-based radar a more viable near-term technology.

Microwave radiometer development is less mature than radar technology. However, the recent introduction of a radiometer that scans and profiles temperature, water vapor, and cloud liquid water, and experimentation with techniques to use radiometers in a horizontal sensing mode, in addition to the more traditional vertical or near-vertical modes, are promising. Microwave radiometers are passive, an advantage to the military, but they lack absolute ranging capability—a disadvantage. Identification of cloud glaciation and drop size with polarization is an additional useful radar and microwave radiometer capability.

Lidar is not considered a viable technology for remote sensing of icing conditions because it cannot sense deeply into optically thick clouds. Remote detection of temperature is possible with microwave radiometers and RASS from the ground, but perhaps only by using microwave radiometers from aircraft. Considerable development is needed in this area.

The most critical needs in operational research are to assess cockpit and aircraft system integration, develop avoid-and-exit protocol, and assess the human factors in using remotely sensed icing information. In addition, remotely sensed icing information must be integrated into weather and air traffic control infrastructures, and aircraft flight envelopes and the hazard of icing to aircraft performance in these envelopes need better definition. Improved absolute and spatial characterization of cloud and precipitation liquid-water content, drop-size spectra, and temperature are needed to develop remote-sensing system specifications. An icing metric must also be developed that will allow the sensed microphysical conditions to be converted into a measure of icing potential for aircraft. Technology development requires refinement of inversion techniques for unambiguously retrieving liquid-water content, drop size, and temperature from clouds and precipitation. These goals can be accomplished with strong leadership and collaboration among federal agencies, including NASA, the FAA, the National Center for Atmospheric Research, NOAA, and DoD. Partnership between government and industry will bring viable technologies to prototype and to market.

2.0 INTRODUCTION

2.1 Purpose

Development of a remote-sensing icing-avoidance avionics system requires assessment of the operational requirements of the system, the environment to be sensed, and the technology available to accomplish the task. This report identifies the state of knowledge, strengths, weaknesses, major issues, barriers, and opportunities, and it identifies the research and investment needed to create a prototype icing remote-sensing system.

2.2 Scope

This report provides a framework for the development of a plan for creating in-flight icing-avoidance remote-sensing systems for use in the national airspace. There are three strategic elements:

- Identifying the operational needs of pilots, operators, manufacturers, and regulators as to functional requirements, system utilization, aircraft integration, and human factors
- Identifying sensing requirements
- Identifying technologies, and their state of development, for an integrated sensing system.

2.3 Goal

This report is intended to provide background information to facilitate the creation of a development plan to improve aircraft operational capabilities and safety in icing environments. This will be accomplished by developing remote-sensing systems that provide pilots with information about the location and intensity of in-flight icing hazards, giving them the ability to avoid and exit icing expediently. This will

- Increase safety
- Reduce delays
- Increase aircraft utilization
- Increase military readiness.

One method of either avoiding or escaping icing is to sense remotely, either from the ground or from aircraft, atmospheric icing potential (Ryerson 1996, 1997, 1998). This requires scanning the airspace ahead of an aircraft for supercooled water and presenting that information to the pilot in a manner consistent with efficient cockpit risk assessment.

Currently, no dedicated system exists for remotely sensing the icing potential in a projected flight path for an individual aircraft. A remote-sensing system that advises pilots of the icing risk ahead of an aircraft will be an information management system that senses the environment, processes the sensed information, and presents it in a useful form. This requires that the proper environmental parameters be sensed with an accuracy suitable for providing useful information, that the information be processed with sufficient speed to assist pilots, and that information be presented in a manner that aids pilots in making icing risk-management decisions.

2.4 Relevance

Current methods of avoiding icing, including meteorological and pilot reports, are extremely ineffective (Erickson 1997). Icing information is not provided with the detail, accuracy, and timeliness needed for commercial and private aircraft to avoid icing conditions efficiently. As a result, either aircraft cannot fly or large areas of potentially flyable airspace must sometimes be avoided because of inadequate spatial and temporal resolution of forecasts. Military aviators and civil aviators in the Far North where bush flying is common also need to be able to avoid icing autonomously because forecasts are often unavailable in operational areas (Owen 1997). In addition, increased use of laminar flow airfoils and more efficient engine designs less tolerant of contaminants make some aircraft more susceptible to icing. As air traffic increases in volume, new aircraft designs are implemented, and new routes are established, more aircraft that are less tolerant to contamination may be exposed to icing. To increase aviation safety and efficiency, and to increase military readiness and air superiority, improved methods of avoiding and exiting icing are needed.

Aircraft flying at 400 knots or greater, which includes most jets, generally do not have icing problems because they typically have heated leading edges and fly above most icing (Taylor 1991). However, jets on approach and departure, 300-kt turboprops, piston aircraft, and helicopters are all susceptible. Turboprops fly exclusively at lower altitudes and are thus exposed to ice for extended periods. Few light piston-engine aircraft have deicing capability. Helicopters are probably the most threatened of all aircraft because of their unique aerodynamics and mission requirements and because they typically lack deicing capability.

Pilots, operators, and manufacturers typically do not know when most aircraft reach their performance limits in icing (Erickson 1997). There are generally few clues provided to the pilot that indicate how close an aircraft is to those limits. This is of particular concern for aircraft operation outside of FAA FAR 25, Appendix C, design guidelines. The result is that many pilots may unknowingly operate their aircraft at or near safety limits when in many icing situations, despite the availability of onboard protection systems.

Fortunately, transport-category aircraft are rarely lost to icing, although there are reported incidents (Engelberg and Bryant 1995), but private general aviation does not fare as well. Aviation magazines carry many reports of private general-aviation icing incidents and accidents. Between 40 and 60 private general-aviation accidents annually are attributed to in-flight structural icing, about 50% of which are fatal (AVEMCO 1983, Taylor 1991). Although about 50% of these are visual flight rule (VFR) pilots in instrument meteorological conditions (IMC)—a pilot training problem—many of the accidents may be preventable with onboard icing-avoidance systems (Bertorelli 1992). Even a VFR pilot may be able to avoid the most serious of icing conditions—freezing drizzle or freezing rain—with onboard remote-sensing icing avoidance capability. An instrument flight rule (IFR) pilot could avoid icing within IMC, or at least avoid conditions that tax aircraft ice-removal systems.

Helicopters flying low-altitude missions to service offshore oil rigs and in search-and-rescue operations, for example, are particularly vulnerable to icing. In addition, limited altitude capability, low speeds, rotating components, and generally low power reserves make them more susceptible to ice than fixed-wing aircraft (Manningham 1991). However, helicopters' low speed and maneuverability may be an asset if they are equipped with an icing-avoidance system because they have more flexible course- and altitude-changing capability than fixed-wing aircraft. As recently as 1995, only one commercial helicopter was icing-certified, the Aerospatiale Super Puma (AHS 1995).

In-flight icing is not generally considered a problem in Army aviation, despite problems in Bosnia, because most missions are flown in warm climates, missions are not flown if ice is predicted, and icing is so infrequent that readiness is little affected. However, about 9% of Army medevac flights in Alaska are canceled due to icing, and medevac commanders give icing avoidance a high priority. Mayer et al. (1984) found about 525 icing-related mishaps in the Navy between 1964 and 1984, with about 70% due to in-flight problems and nearly all due to foreign-object damage from ice. Accident reports in recent years suggest that the Navy has had fewer icing problems, with more reports of hail-impact damage than airframe ice accretion problems, but Lef et al. (1994) state that the Navy is concerned about the icing threat to carrier-launched aircraft and that helicopter icing accidents are not infrequent. Air Force transport aircraft have also experienced icing problems, for example, in tropical cumulus clouds at high altitudes. The Coast Guard reports problems with icing in search-and-rescue and enforcement missions (Yatto 1997).

Military and civilian unmanned aerial vehicles (UAVs) are special cases in need of icing avoidance systems. UAVs, especially high-altitude, long-endurance UAVs, may be required to seek routes through icing conditions autonomously (Siquig 1993). Onboard weather-sensing systems could be coupled with autonomous controls to allow UAVs to avoid or minimize icing, which impacts them more severely than it does conventional aircraft because of their low power and high-efficiency airfoils.

In the future, several changes in flight activity could affect vulnerability to icing:

- Implementation of Free Flight may reduce air traffic control surveillance of aircraft routes, making pilots more responsible for weather avoidance.
- Increased commuter aircraft activity will create more flights by smaller aircraft at lower altitudes and slower speeds, increasing vulnerability to icing.
- Increased military emphasis on helicopters and UAVs, both uniquely vulnerable to icing, is expected.
- Increased air traffic is also expected globally, so to reduce the number of icing accidents the accident rate must decrease (Brown and Dorr 1997).

2.5 Philosophy

Icing remote-sensor development is driven essentially by one question: What icing information does the pilot need to make better risk-management decisions? A remote-sensing system that reports icing potential ahead of an aircraft to a pilot is a decision-support system that provides information needed to make decisions regarding flight safety. Pilots' needs drive the development process because they are the ultimate users of information generated by the system. The development process, however, must work within the restrictions and opportunities provided by the aircraft, regulators, sensing technology, and meteorology.

Because pilot information needs are the primary drivers of the process, an early development requirement should be to determine what pilots need to know. Do pilot information needs change with platform, mission, airspace class, mode of flight (i.e., approach, departure, or cruise), or some other factor? Is a ground-based system sufficient, or would an aircraft-mounted sensing system add significant value? What spatial and temporal resolutions are needed, and how do pilots prefer to view the data—as plan, profile, or perspective views, and as individual temperature and liquid-water content maps, or as composite maps of icing potential? How should icing potential be expressed, and how should hazard areas be identified? Though all of this information is not needed to begin research in all areas, it does set the stage and reduces the possibility of misdirecting research and development. It also allows work to begin early in the research and development process on scenario and training aids, which may help establish the direction of technology development.

Although it may not be absolutely necessary, development of an icing avoidance avionics system also requires an understanding of pilot decision-making processes. The form in which information is delivered to pilots may subconsciously affect their decision-making process (Hansman 1997). Understanding how pilots make decisions for avoiding or coping with in-flight hazards will affect the development of a decision-support system. Appropriate paradigms for icing avoidance may be current fielded thunderstorm and wind-shear avoidance systems. Pilots generally view any information beyond that currently available in the cockpit as useful (Erickson 1997), but the kind of information desired must be identified: too much or inappropriate information could confuse pilots.

The pilot's needs determine the information provided by a remote-sensing system, but the atmospheric environment and the physics of icing and aircraft flight determine what information must be sensed to create the information the pilot needs. Pilots are concerned about flight safety and are thus concerned about the performance of the aircraft should it ice. Aircraft performance changes in response to ice accretion on the airframe. Weather is the phenomenon that causes changes in aircraft performance by providing conditions conducive to ice formation on an airframe. Thus, the ice accretion process may be viewed as an input–process–response system (Fig. 1). Weather is processed by the aircraft to produce ice on the airframe, which, in turn, influences aircraft performance.

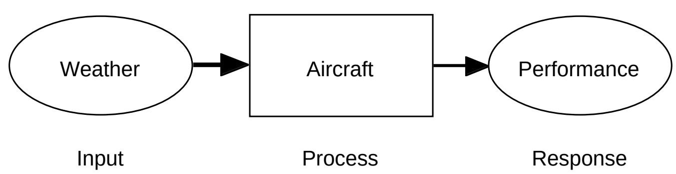

Figure 1. Aircraft icing paradigm.

Sensing requirements are independent of specific aircraft, because different aircraft process identical weather conditions in different ways: The same weather conditions may produce different icing conditions on a light piston-engine aircraft than on a jet transport or a helicopter. And identical weather conditions may produce different icing conditions on an aircraft in different flight configurations depending upon power application, angle of attack, skin temperature, and other factors. Although the meteorological conditions may be identical, the processed information provided by the remote-sensing system should be aircraft-specific to allow the pilot to anticipate potential aircraft performance changes due to icing.

2.6 Organization of this report

Broadly, research and development for remotely detecting icing conditions can be placed in three categories: operations, meteorology, and technology. Operations includes the human/machine interface, regulatory issues, avoid/escape strategies, aircraft integration, training, and terminology. Meteorology involves atmospheric environment and characteristics that must be sensed. Technology refers to the remote-sensing systems that may be able to sense icing potential. Subareas of research and development needed are identified within each primary category. This report gives an overview of the state of the art, describes barriers and opportunities to development, and recommend development directions.

3.0 OPERATIONAL REQUIREMENTS

3.1 Summary

Pilots are risk managers. When it is a question of flight safety, they want clear, unambiguous information about the location and intensity of weather threats before they enter them. A top-level requirement with regard to icing is to provide pilots with a decision-support system specific to the remote sensing of icing potential ahead of aircraft. Standoff guidance about icing potential could be provided from satellite and ground-based sensors uplinking information to the cockpit or from aircraft-mounted remote-sensing systems. However, satellites still do not have the capability of providing high spatial- and temporal-resolution icing information. Ground-based sensing systems at airports would be most cost-effective per aircraft served, protect the most critical phases of flight, and are systems for which sensing technologies are most mature. Aircraft-based systems would be most costly per aircraft and the technologies are least mature, but aircraft would be protected in all phases of flight, especially when arriving or departing from small, remote airports that do not have remote-sensing systems.

Ground-based systems should be developed first, because of their near-term technological maturity and cost effectiveness as an operational test bed, and to protect congested airport approach and departure areas. Satellite-based sensors need continued development to supplement local sensing systems and to provide protection during cruise flight where spatial and temporal detail may not be as critical. Aircraft-based systems need the greatest development, but they offer the greatest potential for providing the information pilots need.

Pilots need information, not data. Thus, remote-sensing systems must provide clear, simple displays that reduce and do not add to flight-management demands in critical approach and departure flight regimes where icing is most frequently encountered. Because wind-shear alert systems have evolved since the development of cockpit resource-management concepts, they may serve as useful analogs for designing an effective pilot interface for icing avoid-and-exit advisory systems. Research is needed in this area. In addition, unlike wind shear, which is a directly sensed threat to aircraft, icing does not occur until aircraft enter icing conditions, process cloud microphysical conditions, and create ice on the airframe (Fig. 1). Thus, icing potential is a virtual phenomenon, and the most appropriate methods for quantifying, analyzing, and displaying the virtual threat must be determined. The types of display, terminology, methods of indicating potential icing intensity, sensor range, resolution, accuracy, and refresh rate and warning time needed are a function of airspace class, aircraft type and configuration, and mode of flight. This mix of conditions needs to be considered in developing optimal pilot information systems, training protocol, and sensing systems.

Cost, weight, space, power, and maintenance are some of the concerns of aircraft manufacturers and operators. The aircraft most needing protection—commuters, helicopters, and light aircraft—offer the fewest of these resources, so for airborne sensing systems, the need is to provide the greatest benefit for the least impact. The spatial and temporal threat of icing is generally small when viewed annually, so it is probable that icing remote-sensing systems will not be installed in lieu of competing avionics or weapons systems. They will probably be used only if mandated or required because of market or extreme safety pressures.

Remote sensors may provide pilots with the location and intensity of icing potential ahead of their aircraft. However, pilots must also be able to determine how this icing potential will affect safety, because a decision to enter or avoid the sensed conditions is a function of the aircraft's ability to operate in icing. Aircraft are certified for flight in icing conditions according to atmospheric criteria specified in FAA FAR 25, Appendix C, but pilots need to know how aircraft respond to conditions outside of Appendix C. They also need to know how much additional icing an iced aircraft can tolerate. That is, they need to know how much ice is necessary to produce unsafe operating conditions. Aircraft may have to be tested outside of Appendix C conditions to determine their operational limits. In addition, the development of smart aircraft-monitoring systems may also be needed to guide the pilot's decision to enter or avoid icing.

An important side benefit of onboard icing remote-sensing systems is the potential for downlinking weather information to other aircraft, air traffic controllers, and meteorologists. Downlinked weather information, from both remote-sensing and in-situ sensors aboard aircraft, will improve temporal and spatial accuracy beyond what is now possible with pilot reports. Accurate downlinked cloud liquid-water content, drop sizes, and temperature will improve icing forecasts and provide more accurate icing warnings for other aircraft. Up- and downlinking of weather information to and from the cockpit are areas of research being addressed by the Advanced General Aviation Technology Experiment (AGATE) program and by NASA Langley Research Center in the Aviation Weather Information (AvWIN) program.

Efficient, cost-effective methods for testing remote-sensing technology, testing display and information-management techniques, and developing avoid-and-exit protocol and training are necessary for development and certification. Sensors may be tested from ground-based test beds and airborne platforms. Ground-based test beds include wind tunnels, spray rigs, and mountain-top test sites. The advantages of ground-based test beds include cost, accessibility, and control of test conditions. Mountain-top test sites allow less control over conditions, but they do provide the variability of natural icing. Wind tunnels and spray rigs cannot provide the spatial conditions necessary for testing remote sensors, but they can be used to test in-situ sensors and the environmental effects of icing conditions on sensors and airfoils. Airborne platforms provide the best environment for testing aircraft-based remote sensors. Overall, a combination of ground and airborne test beds will be necessary to test both ground-based and airborne remote-sensing systems.

3.2 Introduction

Operations establish the functional requirements of a remote-sensing system designed to detect icing. The goal of system development is to improve the safety and efficiency of aircraft operations. However, operations is a complex, multifaceted problem. A comprehensive review of general operational needs in icing environments is presented by Brayton and Hakala (1996).

One element, and ultimately the most important element, of operations has to do with pilots and their needs (Vigeant-Langlois and Hansman 1999). Although pilots are on the leading edge of the icing problem because they are actually within the icing environment, they deal with more than icing. Systems from which pilots seek icing guidance must be designed in a manner that best suits the operational requirements of the cockpit environment and that effectively and efficiently helps pilots make management decisions. This includes the design of the display and information delivery system and training in its use.

3.3 Pilot needs and human factors

Pilots have three concerns about the icing environment (Vigeant-Langlois and Hansman 1999):

- How to recognize that they are approaching or are in icing conditions hazardous to their aircraft
- How to avoid icing
- How to escape icing.

In-flight icing is a frequent topic in pilot safety briefs and popular literature (Buck 1988, Collins 1989, Schuyler 1989, Taylor 1991, Bertorelli 1992, Horne 1994, and others). Over the years, rules of thumb, advice, and regulatory requirements have created ad hoc protocols for icing avoidance and escape. As a result, most pilots manage to avoid forecasted icing by not flying, or by making route deviations to avoid the conditions, or they encounter ice and escape safely through good fortune. Tales of icing mishaps and escape are common fare in winter aviation literature (Creley 1990, McClean 1992). Many pilots do not survive icing encounters because they did not recognize that they were in ice until too late, and they did not have the ability or capability to escape once immersed.

One of the larger causes of this avoidance and escape problem is the quality of icing forecasts. Most pilots who want to avoid icing cannot, because icing forecasts do not have sufficient accuracy as to spatial, temporal, and intensity criteria (Erickson et al. 1996, Green et al. 1996, Stack 1996, Clark 1997). Forecasts are often made conservatively, on the side of safety, to minimize accidents and compensate for inadequacies in forecast procedure. However, this causes aircraft to not fly or to divert when it may not be necessary because large areas forecasted for icing may not have ice or even clouds. As a result, the aviation system is less efficient, though safer.

3.3.1 Pilot needs

Pilots need information for making risk-management decisions about in-flight icing. They want to be able to determine whether they are in or about to enter icing, because icing clues are often not visible from the cockpit windows (Erickson 1997). Pilots also need to know the location of icing and how intense the icing might be without dipping their wings into it, as is now necessary (Green et al. 1996). Onboard, in-situ ice detectors (reactive detection systems) are a solution to the problem of determining exposure to icing for many fixed-wing aircraft and a few helicopters (Bracken et al. 1996), but even these systems require that the aircraft enter icing conditions before determining that they are in hazardous conditions.

Pilots need clear, unambiguous guidelines as to when severe conditions are entered or warning that severe conditions lie ahead with sufficient lead time to avoid them (Erickson 1997). According to Coleman (1996) of the Regional Airline Association, the answer to maintaining safety in icing conditions is to locate severe icing accurately and then avoid it. Because icing forecasts cannot provide the needed accuracy at the present time, remote detection or standoff (prediction detection) systems may (Green et al. 1996).

Standoff guidance of icing conditions ahead of aircraft could be provided in at least three ways, all using a form of remote-sensing system. One method under development utilizes satellite remote-sensing to map icing potential and uplink information to aircraft (Lee and Clark 1995, Vivekanandan et al. 1996, Lee 1997, Thompson et al. 1997, Curry and Liu 1992). Satellite-derived information can be used to delimit areas with liquid water, subfreezing temperatures, and cloud cover. Analyses could be accomplished in near real-time and would provide a useful predictive detection capability.

Another method, also under development, utilizes ground-based sensors at airports to map icing conditions in approach and departure areas (Gary 1983, Decker et al. 1986, Stankov et al. 1992). Remote sensors to detect temperature profiles, cloud boundaries, liquid-water content, drop-size spectra, and cloud phase from the ground are nearly available. Walter and Moynihan (1997) even propose a mobile system for military use. An airport-based system would serve all aircraft, utilize largely existing technologies or technologies that are nearing maturity, and serve the phases of flight most likely to experience icing. It would be a cost-effective approach, considering cost per aircraft served (Owen 1997).

A third system would be an in-flight, aircraft-mounted remote detection system (Sand and Kropfli 1991; Fournier 1993; Siquig 1993; EWA 1996; Ryerson 1996, 1997, 1998). An airborne system would require elements similar to a ground-based system, with the ability to detect temperature, liquid-water content, and drop spectra. However, the technologies may be quite different because of their use on a small moving platform, scanning primarily horizontally, and operating within restricted power and weight limits.

Pilots need better information than is now available, and they require information that is easily understood and provides options (Vigeant-Langlois and Hansman 1999). An ability to see through an icing weather system and map the extent of a threat area would be optimal, but any more information than is now available would be welcome (Clark 1997). A warning time of 1 to 5 minutes, preferably integrated into an existing display system, of areas that are of risk to aircraft would be most useful, and even no warning time may be acceptable (Erickson 1997).

3.3.2 Human factors

Development of icing-avoidance avionics is a human-centered development process because the intent is to display information to pilots. Thus, information needs must be assessed, and perceptual issues vs. display design must be considered (Hansman 1997, Vigeant-Langlois and Hansman 1999). A useful approach to designing a human/machine interface for icing avoidance is to review issues addressed in other weather-avoidance areas. Recent developments of onboard wind-shear alert systems and other weather-avoidance systems, especially since cockpit resource management has been recognized as a consideration in single- and multiple-pilot cockpits, may serve as reasonable analogs. One important finding of cockpit resource-management research has been that automation can cause human error as well as reduce it (Helmreich 1997). Because icing-avoidance systems are likely to be in greatest demand during the approach and departure phases of flight, balancing the distraction against the aid provided by an advisory system is critical to its usefulness. A poorly designed interface may actually produce a hazard to flight, so proper human/machine interface design is nearly as crucial to final success as is the ability to sense cloud microphysics accurately.

Icing is probably a more complex problem than wind shear and convective turbulence because it is less compact geographically, it is a hazard in all modes of flight, and there is significant variation in the ability of different aircraft to cope with the hazard. However, there may be similarities. Wanke and Hansman (1991) evaluated graphical displays of microburst alerts from both ground-based and airborne detection systems. The issues ranged from display clarity to pilot response to alerts. Questions addressed involved the visual clutter of adding alerts to existing navigational displays, value of single- vs. multiple-level intensity display, value of indicating the alert source (ground or airborne), and effect of alert source on pilot procedural response. Active airline pilots were tested in a realistic transport-aircraft flight simulator. The results showed that multi-level intensity displays are desirable, the source of information was not important because confidence was placed in the alert whatever the source, and correlation with other information was not important. The study also suggested needed training areas, because pilots often responded to alerts with evasive action that was inappropriate or not necessary.

The amount of information displayed in the Wanke and Hansman (1991) study did not appear to be an issue. That is not always the situation, however, and it may be related to single- vs. multiple-pilot cockpit environments. For example, Svensson et al. (1997) evaluated the effects of information complexity on fighter pilot performance in the Swedish air force. They found that even moderately complex information, measured by the amount of information provided, interfered with flight tasks. The critical flight measure was an ability to maintain altitude above undulating terrain. When information load increased to more than 8 to 10 items, pilots could no longer integrate information and still fly the airplane. The authors indicate, through numerous examples, that humans have severe limitations in what they can receive, process, and remember, and the 8 to 10 information load items found in this study is consistent with the generally 7 information load items found in many other studies. They conclude that modern technology can provide large quantities of information that often make the pilot feel more confident, but performance is governed by human, not technological, limitations. Information overload can be a serious issue because pilots will either fixate on one, perhaps trivial, problem or lose the ability to ably accomplish any tasks. Though flying in icing may not be as stressful as terrain-following flight in a high-performance aircraft, icing often is most threatening in the busy, critical departure and approach phases of flight.

Another issue for icing displays is the type of graphic image provided to the pilot. Displays may be aircraft-referenced or ground-referenced, and each may have plan, profile, or perspective views. Though perspective views look realistic, plan and profile views are better for decision making (Hansman 1997). Early MIT studies of terrain-avoidance displays indicated that the type of display affects behavior and thus the avoidance strategy used by pilots, for example by avoiding terrain by climbing vs. turning. Aircraft performance characteristics, vertical and horizontal range, resolution, accuracy, scan rate, and sensor limitations also affect the displayed information.

Pilots need information, not data, so the display must be a rendition of the icing environment that allows the pilot to obtain the needed information unambiguously and in a form that promotes appropriate response. One of the issues is 2-D vs. 3-D displays and the way pilots relate to each for different tasks. Cloutier (1997) presented two potential 2-D displays showing plan and profile views of icing potential for helicopter pilots. Boyer (1994) indicated that little research had been done evaluating the effectiveness of 3-D weather displays, and he addressed the benefits and costs of 3-D vs. 2-D displays and conducted an evaluation using student pilots for navigating around weather systems. He concluded that 2-D displays offer advantages for navigating around weather, with few benefits attributable to the 3-D display.

A measure of effectiveness of a look-ahead weather alert system is the warning time provided for pilot reaction. The warning time needed may be a function of airspace class, aircraft type, mission, and mode of flight. Though any warning time, no matter how short, may be helpful (Erickson 1997), there may be minimum warning times that are more acceptable than others. Anderson and Carbaugh (1993) address this problem for wind-shear-alert systems and consider it a critical factor in how pilots judge the value of an alert system. Vigeant-Langlois and Hansman (1999) address warning distances for icing, with commuter pilots reporting as little as 20 nautical miles as sufficient. All other classes of pilots wanted longer warning distances, and thus greater warning times.

According to Hansman (1997), aircraft certified for flight in icing have only to avoid severe icing, whereas aircraft not certified for flight in icing require more decision support for strategic and tactical planning, go/no-go decisions, and escape guidance. A simple pilot decision structure has two options if icing is forecast, either to not go—the risk-adverse path, or to go—the risk-tolerant path. There are three outcomes for the risk-tolerant path:

- Encountering no ice
- Encountering ice but having options for avoiding its effects
- A catastrophic outcome.

In the decision-making process, the risk of making a flight is weighed against the flight's value. For high-risk flights, the incentive to make the flight must be high for it to occur, or options must be available to reduce the risk. The decision to fly into potential icing involves having options for avoidance and escape, such as seeking dry or warm air or turning back or landing at alternates, to ensure a successful outcome. Other possible outcomes are to reach the destination without encountering ice or to have an ice-induced accident. A remote-sensing ice-avoidance system may provide information for exercising options and reducing risk. Escape options are either vertical—finding warm or dry air, or lateral—finding dry air (Vigeant-Langlois and Hansman 1999). Research must be conducted on each of the risk paths described above into how operators and pilots may use in-flight ice detection to make flight decisions. Vigeant-Langlois and Hansman (1999) also indicate that pilots want escape guidance to be displayed in the cockpit.

3.4 Manufacturers and operators

Aircraft operators and manufacturers are concerned with the cost, weight, space, power, maintenance, and training requirements of placing additional avionics packages on aircraft. They are also concerned about the implications of a remote detection system being onboard, for it implies that the aircraft cannot cope with icing (Bond et al. 1997).

Cost is a large issue because aircraft that most need remote ice-detection systems can afford it least—the regional airlines (Owen 1997). In addition, unless a system is extremely inexpensive, remote-detection systems will find little use on light, private aircraft (Vigeant-Langlois and Hansman 1999). This is a significant problem in the Far North where light aircraft operate with no ice protection and with few or inadequate weather advisories (Owen 1997). Even airlines operating large transport-category aircraft are reluctant to use avionics they perceive to be of limited value because, beyond the initial cost, there is the cost of flying it (lost payload) as well as maintenance and training costs.

Weight and space are serious problems, especially for light aircraft and on many smaller civilian and military helicopters. Although these aircraft may not be ice-protected, they may be IFR-rated and thus require the additional security provided by remote ice detection. Single-engine light aircraft have little space and weight reserves and, in addition, there are few locations for sensor arrays since the engine and propeller dominate the front of the fuselage. It may be possible, however, to operate a sensor through the propeller by synchronizing it with the rotating propeller (Kirkpatrick 1970).

Power is also a problem on many aircraft. Larger civilian aircraft and military aircraft carry power-demanding avionics and weapons systems. As a result, if space, weight, or power requirements are large for a remote-sensing system, tradeoffs between other avionics or a weapons system and the remote-sensing system must be considered. The icing remote-sensing system may be avoided because of the small percentage of time that it may actually be used. Military users may also be concerned about the signature provided by systems utilizing active rather than passive remote sensors.

A remote-sensing system designed to detect icing conditions ahead of an aircraft must be inexpensive, small in size, low in weight, and require little power. Though different types of aircraft may use systems of different capabilities to reduce the impact of some of these factors, all development should focus on minimizing these liabilities.

3.5 Regulatory issues, weather forecasting, and traffic management

3.5.1 Functional requirements

Above all, a system designed to detect icing conditions remotely is a pilot decision-support system (Clark 1997). It is a system that senses conditions ahead of an aircraft and translates it into an icing intensity index to advise the pilot whether conditions are threatening to safe flight. Systems could provide air traffic controllers (ATCs) and meteorologists with icing intensity information and measured cloud microphysical parameters. They could upload weather and satellite information from the surface and integrate it with remote-sensor guidance (Bond et al. 1997). They could also use information from onboard in-situ sensors to corroborate remotely sensed information and integrate all sources of information into a comprehensive icing advisory system. Overall, aircraft icing remote-sensing systems could aid pilots, meteorologists, air traffic controllers, dispatchers, and ultimately the public through improved aviation safety.

3.5.2 Regulatory issues

Regulatory agencies are responsible for providing leadership and procedures for maintaining, improving, and enforcing aviation safety. As a result, other than requirements of individual operators and the military, systems for remotely detecting icing may not be used on most aircraft without being required by regulators. Regulatory needs for operating in icing environments have been identified by Brayton and Hakala (1996). Nearly all changes in the regulatory environment that they recommend would be affected by implementation of remote ice-detection systems, and all would need evaluation should onboard remote-sensing systems become available. The areas most affected, and requiring greatest study by regulators, would be weather reporting procedures between aircraft and the ground; automated substitution for standard icing pilot reports; handling procedures for aircraft wishing diversion; flight crew, dispatch, and air traffic control (ATC) training; and icing severity terminology. Aircraft certification to fly in icing conditions probably would not be an issue, because specific aircraft capabilities within icing would not be affected by warning systems; only their ability to avoid and escape would be changed.

3.5.3 Incentives

Regulators determine what kinds of equipment should be mandatory on aircraft in different categories of operation. Because of cost and complexity, unless there are special needs of individual operators, regulators may have to mandate installation of remote-sensing equipment for detecting icing conditions on specific classes of aircraft. Such a mandate would be preceded by a thorough evaluation of remote-sensing system capabilities, with a focus on their ability to enhance safety. Mandates for use on aircraft, or simply certification for those operators voluntarily using systems, would require that regulators consider issues of system integration and protocol compatibility.

3.5.4 National airspace impact

Regulators must determine the impact of remote-sensing systems on operation of the national airspace system, air traffic control, and the Free Flight concept.

3.5.5 Aircraft operational limits in icing

Pilots need to know the potential intensity of icing ahead of their aircraft. They also need to know how their aircraft responds to icing conditions, and they need to know the limits of their aircraft with regard to icing. FAR Part 25, Appendix C, defines icing cloud microphysics for aircraft design. However, if an aircraft is not designed specifically to fly in conditions beyond those described in Appendix C, it is not known whether it can safely operate in those exceedance conditions. If aircraft are not tested in conditions beyond Appendix C, perhaps they should not be sent into those conditions (Hill 1997).

Icing risk varies with aircraft size, aircraft design, and airfoil type. Aircraft manufacturers must identify the icing conditions that are beyond the capabilities of their aircraft. Consideration must be given whether to expand Appendix C conditions or create a new FAR to address these conditions. Presently, pilots do not know if they are flying in conditions within which the aircraft was tested, and they do not know if the icing being experienced will take the aircraft to its limits (Bettcher et al. 1996, Parelon 1996, Erickson 1997, FAA 1997). Although it is not absolutely necessary to the functioning of a remote icing-detection system, providing pilots with information about their aircraft's operational limits and being able to relate information provided by sensing systems to those limits would give pilots more confidence about decisions to avoid or fly through icing.

3.4.6 Weather downlinking

Onboard icing-sensing systems, through immediate and continuous downlinking, could provide forecasters and numerical models with objective and timely temperature, liquid-water content, and drop-size information that is accurate in position. Goals of forecasters at the NWS Aviation Weather Center are to better identify where icing is occurring, identify areas of greatest risk, and determine when icing conditions disappear (Carle 1997). The military has similar concerns (Tucker 1983, Peer 1986, Goe 1997). Downlinking of information gathered onboard would indicate the magnitude and location of icing potential, indicate where there is no icing potential (Vigeant-Langlois and Hansman 1999), and provide improved forecast verification. A program should be organized to formulate standards for integrating ground, satellite, in-situ, and aircraft-based icing information and to establish protocol for auto-reporting to ground and to other aircraft. Regulators could use the information to establish protocol and requirements. Since too much downlinked data could result in confusion rather than clarity and actually decrease the quality of information subsequently provided back to pilots, human-factors specialists should work with pilot and meteorological interests to resolve these problems.

3.5.7 Training

Training is critical to successful use of automated systems. It is needed to provide familiarization with systems and procedures. This will be most important as remote-sensing systems are initially placed in the field to assure that pilots, air traffic controllers, and operators are aware of their operational characteristics. There is often a tendency to over-rely on technology because of apparent belief in its accuracy and reliability (Transport Canada 1996). As a result, cockpit technology tends to reduce vigilance and situational awareness, which, in an icing environment, could be fatal.

Since remote-sensing technology may actually detach pilots from the icing threat because automation tends to increase confidence and reduce situational awareness, there is increasing need to promote training. Training is needed on how the operational characteristics of remote-sensing systems operate and where their abilities and failings lie. This training should be fed by studies about the characteristics of the system, perhaps through work that would have been done to verify system capability (Baum and Seymour 1980). In addition, there must be training on how to respond when an icing warning is displayed. Human-factors research has addressed this issue for wind shear and terrain-avoidance systems and recently for icing (Hansman 1997, Vigeant-Langlois and Hansman 1999). However, research is needed to determine the most appropriate avoidance and escape procedures for various classes of aircraft in different types of airspace and meteorological conditions. Establishing training standards and best management practices is a regulatory and operator responsibility.

3.6 Test beds and platforms

Efficient, cost-effective methods of testing elements of remote-sensing systems, and full systems, are needed in the development stage under conditions representative of the operating environment. Ground-based test systems are generally less expensive than airborne platforms, so their use should be encouraged at all stages of development until full testing on aircraft is required.

Airborne platforms, spray tankers, and perhaps mountain-top observatories should be used to test prototypes of individual sensors and of entire remote-sensing systems. Remote-sensing systems intended for placement on aircraft must be capable of sensing horizontally ahead of the aircraft and above, below, and to the sides of the flight path, so they should be tested in the same position as they will be used aboard aircraft to provide confident results (Ryerson et al., 2000). Mountain-top facilities that have potential testing capabilities include the Desert Research Institute's Storm Peak Laboratory; Elk Mountain, operated by the University of Wyoming; Whiteface Mountain Observatory, operated by the State University of New York, Albany; and Mt. Washington Observatory, N.H. (Ryerson et al., in prep.). An advantage of mountain-top facilities is the availability of natural icing conditions. Likewise, a disadvantage of natural icing is the lack of control over conditions. Research aircraft available for testing may include the NASA Twin Otter, the NRC Twin Otter and Convair 580, the NCAR King Air, and aircraft from the University of Wyoming, the University of North Dakota, and a variety of private companies (Marcotte et al. 1996). The Air Force tanker spray rig has been removed from service, but the Army still operates its Helicopter Icing Spray System (HISS) from Fort Rucker, Alabama.

Flight simulators may also provide information useful for establishing sensor system characteristics. For example, pilots' abilities to react within given warning times provides information for establishing sensing range and update frequency.

4.0 METEOROLOGICAL SENSING REQUIREMENTS

4.1 Summary

The development of systems to measure icing potential remotely and in situ requires an understanding of the medium being sensed: the atmosphere and its thermal and liquid characteristics must be understood with regard to the absolute magnitude of conditions and their spatial distribution. This information is needed to evaluate the feasibility of sensing and avoiding icing potential, to design instruments to sense conditions, and to develop methods of avoiding and exiting icing conditions. The atmosphere must be carefully characterized with regard to icing potential to develop sensors and training protocol, to create terminology for advising pilots, and to provide better icing forecasts. Characterization is needed at all scales from the submesoscale to the global scale, although the synoptic scale is probably best understood with regard to icing.*

Attempts to characterize the icing atmosphere, liquid-water content, drop size, and temperature have been conducted since the 1940s with a large range of instruments, from multicylinders that provide integrated measurements to current electro-optical systems that provide measurements with high temporal resolution. Thousands of research flight hours have resulted in a general understanding of the magnitude of liquid-water contents, and their spatial patterns, that can be encountered by aircraft. For example, it is understood that higher liquid-water contents are generally found in cumuliform rather than in stratiform clouds, that summer supercooled liquid-water contents are highest, and that liquid water is generally more "cellular" than homogeneous over thousands of square kilometers. Studies have also demonstrated that icing conditions, for liquid water and drop size, are extremely variable and difficult to generalize. It is also recognized, though not necessarily widely, that FAR 25, Appendix C, conditions are only representative values for engineering design purposes and are not intended to represent the actual character of the icing atmosphere as encountered by an aircraft.

The characterization of the icing atmosphere has been accomplished somewhat randomly because of the cost of airborne research projects. Each program has a specific focus, so flight hours are typically consumed trying to answer the primary research questions of the project. A large-scale monitoring program dedicated to the characterization of icing conditions would allow large geographic areas, with weather conditions experienced by most of the nation, to be sampled consistently and frequently to produce information that is statistically valid. Work by Cooper et al. (1982) and Sand et al. (1984), by the Canadian Freezing Drizzle Experiment (CFDE), and by the NASA Glenn Research Center during the winters of 1996–1997, 1997–1998, and 1998–1999 (Miller et al. 1998) have come closest to the ideal of covering large geographic areas with modern, carefully calibrated instrumentation. One way to do this would be to instrument commercial or military aircraft that fly large numbers of hours, as Perkins (1952) did, enabling a representative sample of icing conditions to be made nationwide and reported through a system such as ACARS (Aircraft Communications and Reporting System). Ground-based remote-sensing systems installed at airports to protect terminal areas may also be able to provide characterization information similar to that of in-flight programs. This is another argument for accelerating airport-based remote-sensing icing-avoidance systems. Finally, icing radiosondes are available for measuring supercooled liquid water with height within clouds (Hill 1994). Such radiosondes, fielded nationally by the NWS, could improve icing forecasts and the characterization of supercooled cloud water.

Cloud liquid water is generally better understood

* Personal communication, M. Politovich, National Center for Atmospheric Research, Boulder, Colorado, 1997.

than is drop size. Nevertheless, the magnitude, distribution, and organization of supercooled liquid water in 3-D space is still only generally understood, especially with regard to the conditions that aircraft typically encounter. A large component of the problem within supercooled clouds is glaciation. Though attempts have been made to model and measure glaciation to develop a better understanding of the process, it is still not possible to predict accurately whether a given cloud is glaciated, when it will glaciate, and how much of the total water content is ice. Some remote sensors are sensitive primarily to liquid water, such as microwave radiometers, and for users of these systems, mixed-phase clouds are of little concern. However, mixed-phase conditions may enhance the ability of radar to detect liquid water, so the glaciation process needs to be better understood.

Although less important than liquid-water content for determining the amount of ice to form on an aircraft, drop size, and especially supercooled large drops (SLDs), determine the location and shape of ice formations. Thus, drop size may have a larger impact on iced aircraft aerodynamics than liquid-water content does. Drop size is also a more difficult parameter to measure than liquid water, and characterization is therefore less complete than for liquid water. Cloud droplet size varies with cloud type, cloud dynamics, location within clouds, from cloud to cloud, with the season, air-mass origin, and other factors. Drop sizes are often characterized by the median volume diameter (MVD), which assumes a unimodal drop-size distribution. This may not always be the situation, especially when SLDs are present.

The shape of the drop-size distribution must be carefully sensed and characterized. This is especially important for SLDs. Instruments that count drops, such as optical array probes, have the best probability of successfully characterizing drop size. Characterizations of drop size conducted concurrently with liquid-water measurements will provide relationships between the two and to atmospheric dynamics. Drops are usually smaller within stratiform than within cumuliform clouds, but more emphasis should be placed on explicit drop-size measurements and, at least, characterization of the drop-size spectra.

The need to characterize SLDs is even more critical than characterizing smaller drops because of the danger SLDs present to aircraft and because far less is currently known about them than about smaller drops. Flight programs to measure SLD characteristics, such as the Canadian CFDE project and the NASA Glenn Research Center SLD program, should be continued and expanded. Ground-based programs may also be useful for characterizing conditions aloft. For example, sleet, freezing drizzle, and freezing rain at the surface are often accompanied by freezing precipitation aloft. Utilization of ASOS (Automated Surface Observing System) observations at over 600 locations nationally (Ramsay 1997), which observe freezing rain, could improve understanding of the location, spatial patterns, frequency, and magnitude of SLDs.

Proponents of in-flight remote-sensing systems have argued that outside air-temperature measurements made at the fuselage are adequate for temperature characterization ahead of the aircraft. Though this may be generally true in cruise at constant-altitude flight, it is not true where icing is most likely to occur: within storms and in the climb-out and descent phases of flight. Air temperature changes most rapidly in the vertical and within storm systems. Storms and lower altitudes are also where supercooled water is more frequent, so the reliability of outside air-temperature measurements for predicting temperature ahead of the aircraft is least where the need is greatest. Thermal lag also occurs as snow falls into warm air and melts, and as rain falls into colder air and supercools, making drop temperature unknown even if air temperature is known. In addition, evidence from a few studies suggests that temperature does fluctuate considerably within cloud masses and from cloud to cloud and from clear to cloud. Air-temperature fluctuation, especially near 0°C, must be better characterized within clouds and near frontal surfaces. Radiosonde observations and in-flight measurements from existing flight programs can provide most of this information.

The spatial structure and the size of icing areas have not been characterized. Spatial patterns of icing must be characterized at all scales, from global to submesoscale, but spatial patterns are perhaps best understood at the synoptic scale. The horizontal extents of icing specified in FAR 25, Appendix C, do not imply the overall dimensions of icing cloud systems. Overall, little work has been conducted in this area, with the best characterizations being by Cooper at al. (1982) and by the Canadian CFDE program (Cober et al. 1996b).

Cloud microphysics are a focus of several large federally funded research programs, and icing remote-sensing researchers should partner with these teams to accomplish objectives more efficiently. For example, the DoE Atmospheric Radiation Measurement (ARM) Program monitors cloud microphysics to determine the effects of cloud cover, type, height, and phase on global radiation budgets. The ARM program maintains field sites in Oklahoma and on the North Slope of Alaska. Remote sensing of clouds is one of their tools, and NOAA ETL has been a participant in this capacity. The Global Energy and Water Cycle Experiment (GEWEX), part of the World Climate Research Program, also has a cloud microphysics component that may be of value to aircraft-icing remote-sensing research.

Finally, experiments are being conducted by federal, state, and private groups to augment precipitation (cloud seeding). This often involves monitoring of cloud microphysics. Efforts should be made to interact with these groups and perhaps to conduct coordinated research.

Characterization requires reliable and accurate instrumentation for making in-situ measurements. The ideal instrumentation for measuring cloud microphysics would be similar in character to instruments currently used on aircraft for determining airspeed and outside air temperature: generally small, inexpensive, accurate, robust, maintenance-free, and unobtrusive. A focused effort is needed to simplify and miniaturize current instrumentation, but efforts should also be made to completely rethink cloud microphysics instrumentation and to design and develop completely new concepts.

Finally, icing terminology needs improvement. This is being addressed in the FAA Inflight Aircraft Icing Plan (FAA 1997). Currently, icing reports and forecasts are not purely meteorological but include the aircraft. Though practical, because pilots observe how icing is affecting their aircraft, the current terminology is not effective because it does not utilize purely meteorological information to evaluate icing intensity. The aircraft must be separated from weather to evaluate icing conditions objectively and unambiguously.

4.2 Introduction

Information required to assess in-flight aviation icing hazard is derived from measurements of the atmospheric conditions that create ice on aircraft. In order of importance, those conditions are cloud or precipitation liquid-water content, drop temperature, and drop size.* Of these three conditions, liquid water is most important because it is the material that creates ice on the aircraft. Liquid-water magnitude varies widely, both spatially and temporally, so it must be measured continuously.

Droplet temperature is the second most important atmospheric condition affecting icing; it determines in part whether liquid water will freeze on an aircraft structure. Air temperature (static and total temperature are not distinguished here) may serve as a surrogate for droplet temperature, especially if droplets are so small that their fall speed allows them to maintain a temperature nearly that of the surrounding atmosphere. However, snow or graupel falling into a warm layer may melt or partially melt, resulting in particle temperatures colder than the air in the warm layer. If the particles or droplets then fall into colder air below, they will be warmer than the air. Air temperature may be relatively constant over large horizontal distances, but it may also fluctuate considerably within clouds and from cloud to cloud. In addition, temperature may change rapidly within frontal systems and in the vertical, as experienced by aircraft when changing altitude rapidly upon departing or approaching terminal areas.

Liquid-water drop-size spectra determine the location of drop impingement on airframe structures, the type of ice that forms, the shape of ice that forms, and the location of ice on the airframe as a result of runback. Runback is caused by supercooled large-drop impingement and flow along the airfoil chord causing freezing on areas of the airfoil unprotected by deicing equipment. Runback has become a critical problem, especially with respect to SLDs within the drizzle size range (typically diameters of 50 to 500 μm). Runback and formation of an ice ridge immediately aft of the boot-protected leading edge is believed to be the cause of the ATR-72 crash in Roselawn, Indiana, in October 1994 (NTSB 1996). The overall characterization of SLDs vs. smaller drop sizes is relatively poorly understood, so special emphasis should be placed on characterizing the SLD environment.*

Liquid water, drop temperature, and the drop-size spectra are the most important indicators of in-flight aircraft icing potential, and thus the most important conditions to characterize for the development of the sensing needs of remote-sensing systems. However, it may also be useful to sense conditions that are not critical to icing potential but that may serve as surrogates for the other conditions. For example, range-resolved remote sensing of air temperature or droplet temperature may prove to be the most difficult remote-sensing challenge. Whether clouds are glaciated or partially glaciated, or mixed-phase, may provide an indication of whether liquid-water temperatures are warmer or colder than freezing, so the ability to detect ice within clouds may serve as a surrogate binary temperature indication of above- or below-freezing conditions. However, little is known about the glaciation process and the probability of glaciation at given temperatures below freezing. Nevertheless, characterization of cloud glaciation with temperature, to determine if it would be a meaningful surrogate for temperature, may be useful.

The magnitudes of liquid-water content, temperature, and drop-size spectra must be characterized to provide specifications for remote-sensing technology. The spatial variability of these conditions must also be characterized. Characterization is needed at the mesoscale (~10^4–10^6-m scale), synoptic scale (~10^6-m scale), and global scale, although for different reasons, depending on the scale. Characterization of spatial variability

* Personal communication, M. Politovich, National Center for Atmospheric Research, Boulder, Colorado, 1997.

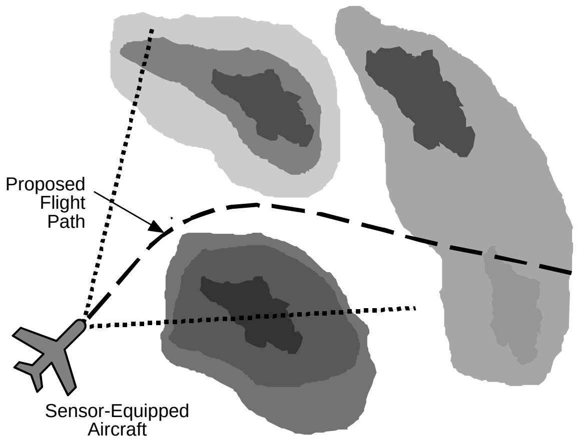

Figure 2. Sensing range affects avoid-and-exit capability.

may provide indications of the range and spatial resolution needed by remote-sensing systems. The ability of a system to sense completely through typical icing storm areas, for example, would provide aircraft with avoidance capability without the risk of entrapment (Kirkpatrick 1970) (Fig. 2). In addition, if icing potential is nearly uniform spatially at the submesoscale, then remote-sensing capabilities may not be practical for avoiding or escaping icing. Spatial characteristics at the synoptic scale will indicate what portions of storms provide the greatest icing threat and indicate where remote-sensing systems are most needed. Global-scale patterns of icing indicate where icing threats and the needs for remote-sensing capabilities are greatest.

4.3 Characterization needs

Characterization of the dynamic range of liquid water, drop size, and temperature are needed to establish sensing specifications for hardware development. The general ranges of conditions that could be observed are generally understood (Pruppacher and Klett 1997, Rogers and Yau 1989, Fletcher 1962), but the absolute ranges of conditions within icing clouds, and the ranges of conditions necessary to produce dangerous ice accretions on aircraft under a full range of flight and design conditions, are not well known.

4.3.1 Liquid-water content

FAR 25, Appendix C (FAA 1991), defines liquid-water content and mean effective drop diameter (similar to the median volume diameter [MVD]) from the surface to 6707 m for stratiform clouds and from 1220 m to 6707 m for cumuliform clouds. This is the minimum standard to which all aircraft ice protection is designed and may be the minimum standard to which remote-sensing systems should be designed. However, although horizontal extent is factored into Appendix C (as a function of cloud type), allowing for larger liquid-water contents in shorter distances, Appendix C represents only integrated liquid-water contents over distances and does not address maxima or minima that can occur within those distances. That is, "pockets" of liquid-water content can be much larger or smaller than the integrated values within a distance represented by Appendix C. According to Masters (1983), the original intent of Appendix C was to represent averaged liquid-water content values during exposure over varying distances, so Appendix C is only a starting point for remote-sensing system specification. Appendix C is effective, within its limits, for creating ice-protection system specifications as long as instantaneous values of liquid water are of no concern, but it is not as effective for determining the maximum and minimum liquid-water values that may be experienced along a given route of flight. For this reason, it is necessary to review field measurements within icing conditions to determine the absolute range of conditions that can be experienced. In addition, the range of conditions with greatest impact on aircraft operations must be considered for studies of the effect of icing on in-flight aircraft performance (Jeck 1998).

The National Advisory Committee for Aeronautics (NACA) Lewis Flight Propulsion Laboratory and Ames Aeronautical Laboratory conducted many research flights within stratus and cumulus clouds from 1945 through 1950 (Lewis et al. 1947, Lewis and Hoecker 1948, Kline 1949, Kline and Walker 1951). Cloud liquid-water content was measured with rotating multicylinders and a rotating-disk icing-rate meter. Rotating-multicylinder and icing-disk measurements are integrated over periods of minutes, so absolute magnitudes over shorter periods, and thus distances, are not well identified. Nevertheless, one flight program provided maximum liquid-water contents of 0.28 g m^{-3} and 0.76 g m^{-3} for stratus and cumulus clouds, respectively, and 90% of the measurements measured less than 0.5 g m^{-3} in stratus clouds and less than 1.2 g m^{-3} in cumulus clouds (Lewis et al. 1947). Flights over the Great Lakes measured liquid-water contents ranging from 0.05 g m^{-3} to 0.57 g m^{-3} with a median of 0.22 g m^{-3} and a mean of 0.19 g m^{-3} (Kline 1949). Ninety percent of liquid-water contents were less than 0.40 g m^{-3}, and 50% of all cases were less than 0.18 g m^{-3}. Thirty-seven research flights over most of the northern United States measured mean values of maximum liquid-water contents averaged over distances of 0.5, 3.0, 15, and 60 miles of 1.05, 0.63, 0.33, and 0.14 g m^{-3} for cumulus clouds, and 0.44, 0.27, 0.16, and 0.08 g m^{-3} for stratus clouds. Finally, flights in stratiform clouds yielded a maximum liquid-water content of 1.30 g m^{-3}, with 90% of measurements less than 0.54 g m^{-3} and 50% less than 0.30 g m^{-3} (Kline and Walker 1951). Large values were typically sought during these flights for establishing engineering standards.

Perkins (1952) instrumented with icing rate meters four United Airlines DC-4 aircraft that flew from New York City to San Francisco from January through May 1951. Of a total of 1120 hours of flight time on typical commercial routes and altitudes, icing was encountered 1.5% of the time. Maximum liquid-water contents did not exceed 1.0 g m^{-3}, and 80% of measurements were less than 0.4 g m^{-3}.

In March 1979, Jeck (1980) made in-cloud liquid-water measurements over Lake Michigan and in the vicinity of Lake Erie. He compared instrumentation used in research flights from the 1940s and 1950s to then-current instrumentation and discussed sources of measurement error when using multicylinders to measure liquid water. The most significant problem was runoff due to incomplete freezing of water impinging upon the cylinders. This occurred when the proper combinations of air temperature and liquid-water content caused the ice temperature to remain at 0°C, the so-called "Ludlum" limit. Jeck mounted a Johnson–Williams hot-wire liquid-water probe that measured liquid water accurately only when drop sizes were smaller than 30 μm (due to design limitations) on a Lockheed Super Constellation aircraft. Measured liquid-water contents were somewhat smaller than historical measurements, in part because his measurements were in the lower portions of stratus clouds, whereas earlier measurements sought the largest values typically encountered, near cloud tops. On the Jeck flights, icing generally did not occur on the aircraft when liquid-water contents were less than 0.08 to 0.10 g m^{-3}. In stratus clouds less than 1524 m agl, 95% of all liquid-water measurements were less than 0.6 g m^{-3}.

In a comprehensive review, Cooper et al. (1982) and Sand et al. (1984) summarized five years of flights made with modern instrumentation by the University of Wyoming King Air. Over 98% of summer and winter and continental and coastal cloud liquid-water measurements—423,787 seconds of measurements with a Johnson–Williams hot-wire liquid-water probe and a forward-scattering spectrometer probe (FSSP)—were less than 1.0 g m^{-3}, and only 0.2% of samples exceeded 2.0 g m^{-3}. Liquid-water contents nearly as high as 3.0 g m^{-3} were encountered, but in less than 0.01% of all measurements.

Jeck (1983) and Masters (1983) compiled a new database of supercooled cloud properties up to 3049 m from about 12,955 km of icing observations using a mix of old and new measurement technology, from multicylinders to newer optical and hot-wire instrumentation. This database was constructed to address the different conditions experienced by light aircraft and helicopters below 3049 m. Supercooled liquid-water contents of up to 1.7 g m^{-3} were found, but 99% of values were less than 1.1 g m^{-3}, and 95% were less than 0.6 g m^{-3} for all cloud types. Larger liquid-water contents are theoretically possible below 3049 m, but values greater than 2.2 g m^{-3} are not likely. Liquid-water values were largest in cumuliform clouds and behind cold fronts in maritime air.

Jeck (1982) also sorted the database described above (Jeck 1983) according to synoptic situation and air-mass category. The resulting liquid-water contents represent average values over uniform cloud intervals of more than 1 km, so peak liquid-water values are not represented. In general, modern data liquid-water contents were 1.1 to 1.2 g m^{-3} in cumulus clouds within lake-effect areas, modified continental air masses, high-pressure areas without fronts, and in maritime air masses. Liquid-water contents were lowest, 0.2 to 0.4 g m^{-3}, in warm frontal stratus clouds, occluded-front stratus clouds, cold-front cumulus clouds, and upslope stratus clouds.

Jeck later expanded the database for icing conditions below 3049 m to include all altitudes and presented seasonal analyses of liquid-water content for design purposes (Jeck 1989). Seasonal liquid-water magnitudes were isolated not by calendar date, but by grouping measurements by the height of the freezing level, with lower freezing levels occurring during winter conditions. Freezing levels below 1524 m agl were used for winter conditions and above 3049 m for summer conditions. Nearly 85% of stratus cloud occurrences were below 3049 m, with the largest liquid-water contents, maximizing near 0.9 g m^{-3}, occurring near 1524 m for warm and cold seasons. Liquid-water content was less than 0.3 g m^{-3} 90% of the time in the stratus. More than 50% of convective clouds occurred above 3049 m, and cold-season convective clouds typically had liquid-water contents of less than 2.0 g m^{-3}, with this maximum occurring near 3659 m. Summer convective clouds, however, had maximum supercooled liquid-water contents approaching 5.0 g m^{-3}, but only above 6098 m.

In a review of the state of knowledge of aircraft icing conditions from around the globe, Hoffman (1984) stated that icing occurs within liquid-water contents of 0.01g m^{-3} to 6.0 g m^{-3}, though values larger than 2.5 g m^{-3} are found only in tropical cumulonimbus clouds. At any given altitude, liquid water within stratus clouds can vary between 0.01 to 1.0 g m^{-3}, and in cumulus clouds it can vary between 0.01 and 1.7 g m^{-3}.

Twenty-five flights measuring liquid water in stratocumulus clouds in Germany with a Johnson–Williams probe indicated that liquid-water contents varied from 0.05 to 0.45 g m^{-3} (Hoffman et al. 1986). Integration distances were 18.5 km, so the values do not represent maxima encountered during flight.

Telford (1988) analyzed the causes of instability and the loss of a Desert Research Institute research aircraft measuring layered cloud properties in the Sierra Nevada. Extreme icing was associated with the crash, and liquid-water contents were measured from 0.2 g m^{-3} to a maximum of 1.4 g m^{-3} prior to the crash. Measurements were instantaneous and were made with an FSSP and a Johnson–Williams probe.

In a detailed study of a winter storm and shallow cold-front passage in the Denver area, Politovich and Bernstein (1995) measured unusually high liquid-water contents for that area in stratiform clouds of 0.6 g m^{-3}. Severe icing was also reported by the research aircraft.

During the second Canadian Atlantic Storms Program (CASP), Cober et al. (1995) reported 3745 supercooled liquid-water content measurements within an 800-km radius of Halifax, Nova Scotia, within stratiform and "system" clouds such as through cold fronts, warm fronts, and low-pressure areas. Clouds of oceanic and continental origin were included. Though few comparisons of liquid water in maritime vs. continental clouds have been conducted specifically with regard to aircraft icing, in general, liquid-water contents are similar for continental and marine clouds of a given genera (Rogers and Yau 1989). Cober et al. (1996a) also found that liquid water varied little between cloud types, except for larger liquid-water-content standard deviations in system clouds. Median supercooled liquid-water content was 0.11 g m^{-3}, with supercooled liquid-water content exceeding 0.94 g m^{-3} only 0.01% of the time, similar to conditions measured by Sand et al. (1984) over the Great Lakes and California in winter. Stewart et al. (1996) measured supercooled liquid-water contents of warm and cold fronts off the Nova Scotia coast. Cloud types are not provided, but the measurements were made with modern optical instruments. Maximum supercooled liquid-water contents were not greater than 0.9 g m^{-3}, and typically they were less than 0.3 g m^{-3}.

Pruppacher and Klett (1997) summarize characteristic liquid-water contents found in clouds by genera, warning that liquid-water content typically varies strongly from cloud to cloud. Early-stage cumulus typically have 0.2 to 0.5 g m^{-3}, later-stage cumulus 0.5 to 1.0 g m^{-3}, and stratus and stratocumulus 0.1 to 0.5 g m^{-3}. Cumulus with strong updrafts have liquid-water contents up to 5.0 g m^{-3}. Though these measurements were made in warm and cold conditions, the tops of cumulus clouds typically have the highest liquid-water contents, which, in the tropics, are often supercooled and produce significant icing.

It is evident that modern measurements taken at short time intervals are necessary to evaluate properly the true range of supercooled liquid-water contents that may be encountered. Though general values are known, most older measurements were made over rather long averaging distances. Nearly instantaneous measurements, on the order of one measurement each second (150 m for a 300-kt research aircraft), provide high resolution. Though the granularity of cloud liquid water is undoubtedly finer, higher resolution would not be necessary for developing remote-sensor specifications.

Liquid-water content has been measured during field programs with modern instrumentation at as fine as 1-second intervals. Examples include ASTEX, the Atlantic Stratocumulus Transition Experiment; FIRE, the First International Satellite Cloud Climatology Project Regional Experiment; the U.S. DoE ARM campaign, Enhanced Shortwave Experiment; and many other smaller programs. These data could be reanalyzed for remote-sensing purposes if they could be acquired. In addition, new flights should be made with better instrumentation.

4.3.2 Cloud drop-size spectra

Liquid water is delivered to aircraft surfaces as discrete drops varying in diameter from only a few microns at the smallest diameter to over 4000 μm in rain drops (Fletcher 1962, Pruppacher and Klett 1997, Rogers and Yau 1989, Willis and Tattelman 1989). Drop size has several important roles in aircraft icing.

One effect of drop size on airframe icing is its influence on the amount of water collected. The amount of liquid water delivered to an airframe surface is a function of the collection efficiency of that surface as affected by the relative speed between the surface and the drop, the radius of the surface, and the drop diameter. As relative wind speed increases, drop size increases, and as surface radius decreases, droplet collection efficiency increases. As a result, smaller drops are carried over an airfoil surface to impact aft of the leading edge, whereas larger drops impact closer to the leading edge. Objects with a large radius are preferentially impacted by large drops rather than by small drops. As a result, the amount of liquid water delivered to a specific portion of an airframe surface is a function of the liquid water residing within that portion of the total cloud drop-size spectrum striking the surface. This ignores runback and other effects that occur after drops impinge upon the surface.

A second effect of drop size is upon the type and shape of ice that forms on the airframe surface (Hansman 1985, FAA 1991, Shah et al. 1998). Depending upon a variety of factors, including the amount of liquid water impinging on a portion of airframe over a unit of time and the collection efficiency of the icing surface as a function of the drop-size distribution, the type and shape of the ice accretion will vary considerably. Low liquid-water contents at low temperatures and small drop size tend to create rime ice, and larger liquid-water contents in warmer temperatures and larger drops tend to produce clear ice (FAA 1991). Rime tends to produce an ice surface that conforms generally to the shape of the airfoil. Clear ice may create a smooth surface, or it creates "horns" near the leading edge that have a large impact on drag and airfoil lift. As drop size increases within clear-ice conditions, the size of the accretion increases, the impingement limits increase in area, and the horns tend to form farther back on the airfoil (FAA 1991). Overall, according to Sand et al. (1984) and Politovich (1989), drops larger than 30 µm in diameter have a greater effect on flight than smaller droplets.

A third effect of drop size is runback. Although runback may occur over a large range of cloud drop sizes, depending upon temperature and liquid-water content, runback becomes more serious when the drizzle-size regime is entered, at about 50 µm. Here, all water does not freeze near its impingement location—some runs back and freezes beyond ice-protected areas of the leading edge. This often creates an ice ridge or roughens wing surfaces, significantly altering airfoil aerodynamics and aircraft performance.

Cloud droplet size varies by cloud genera, from cloud to cloud, by season, and with location within clouds. For example, the largest drops in growing, nonprecipitating cumulus clouds typically occur near the center and top of the cloud within updrafts. Smaller drops are found near the cloud base and near the cloud perimeter where dry air entrainment causes evaporation of drops (FAA 1991). Overall, drop size is controlled by evaporation, collision–coalescence, curvature and solute effects, the Bergeron process, and the number and type of cloud condensation nuclei present (Miller and Anthes 1980). As an example, maritime clouds of a given genera typically exhibit broader drop-size spectra than do continental clouds due to differences in the type, number, and size of cloud condensation nuclei (Rogers and Yau 1989).

Cloud drop-size spectra are typically characterized by the median volume diameter (MVD), the drop size where one-half of the spectrum's water volume resides within smaller-diameter droplets and the other half resides within larger droplets. Internal cloud dynamics may create bimodal drop-size distributions, observed in most cloud types in most climatic regimes (Pruppacher and Klett 1997, Politovich and Vali 1983). Bimodal distributions are not properly represented by a single MVD, however, which relies on a unimodal distribution. The average collection efficiency of a drop-size spectrum around a median volume diameter is generally quite close to the collection efficiency of the MVD. However, the MVD alone does not describe the shape of the drop-size distribution, nor does it adequately describe where collection efficiency effects will cause ice accretion on the airframe (Newton 1979, Cooper et al. 1982).

Early measurements of drop-size spectra were made either with oiled or soot-covered slides or with the use of rotating multicylinders. Slides were difficult to use in high wind speeds, though they were occasionally used as late as the 1960s (Warner 1969). Usually, rotating multicylinders, developed in the early 1940s at Mt. Washington Observatory, were used instead of slides, and they are still in use (FAA 1991, Howe 1991). Multicylinders provide an indication of the shape of the drop-size spectra by utilizing curves developed from theory by Langmuir and Blodgett (1946) using the collection efficiency of various-diameter cylinders for given wind speeds and drop sizes. From these curves, and the amount of ice collecting on each cylinder, the MVD can be estimated. However, serious errors in MVD estimation could occur with multicylinder use in large-droplet situations, where MVDs approach 30 µm or larger (Jeck 1980).

Drop-size spectra were measured coincidentally with liquid-water content in most experiments. The database created by Jeck (1980) at the Naval Research Labs, in cooperation with the FAA, is probably the most comprehensive available. Jeck (1983) and Masters (1983) summarized older and modern measurements both below 3049 m and at all levels of the atmosphere. Jeck (1983) indicates that below 3049 m, average MVDs measured with multicylinder and newer optical instruments, for supercooled layer clouds, are about 13 µm and for convective clouds they are 18 µm. MVD also shows temperature dependence, with MVD increasing from 10 µm to about 30 µm in stratiform clouds as temperature increases from –25°C to 0°C. Jeck (1982) also observed that MVD generally increases with altitude in single-layer clouds below 3049 m.

Jeck (1983) questions the use of a minimum MVD of 15 µm in FAR 25, Appendix C, considering analyses of the database of cloud properties below 3049 m (Jeck 1980). Masters (1983) and Jeck (1983) both provide diagrams from this database showing MVDs in icing clouds well below 15 µm.

A summary of five years of cloud measurements by the University of Wyoming (Sand et al. 1984) showed MVDs ranged from 5 to 40 µm, with a characteristic MVD of about 15 µm. The smallest MVDs were measured during the winter over the Great Lakes and the Great Plains, with the largest MVDs in the summer over the Great Lakes and Illinois and in the winter over Florida. Droplets were smaller in the Great Lakes and Illinois areas because of low liquid-water contents, according to Sand et al. (1984). No relationship was found between icing effects on aircraft performance, a Beech King Air, and the MVDs that produced the ice. Only MVDs larger than 40 µm, reaching into the supercooled large-drop regime, affected aircraft performance.

Roebber (1988), in a review of icing potential on helicopters and fixed-wing aircraft off the east coast of Canada, presents statistics of drop sizes encountered during icing and reported by the Royal Canadian Air Force. The MVDs of convective clouds were between 18 and 21 µm and for layered clouds near 12 µm, but MVDs as large as 50 µm were generally observed in convective clouds, and as large as 40 µm in layered clouds.

Jeck (1989) summarizes MVDs from his FAA/NRL icing database for clouds at all altitudes. Mean MVDs are 13 µm for layer clouds and 17 µm for convective clouds. The range of MVDs within the database, by general cloud type, are 7–21 µm for layer clouds and 10–26 µm for convective clouds.

Cober et al. (1995) reported on 31 flights into Canadian east coast winter storms over the North Atlantic Ocean and created a high-quality database of those flights. Flights were made into fronts, low-pressure areas, and stratus clouds. The average MVD for all clouds was 18 µm: 16 µm for low-level stratus clouds and 20 µm for “system” clouds. These measurements compare well with earlier measurements in the area, according to Cober et al. (1995), and with measurements by Sand et al. (1984).

Politovich and Bernstein (1995) investigated the production and depletion of supercooled liquid water in a February 1990 winter storm in the Denver area. Stratiform clouds associated with a cold-front passage created mean droplet diameters of 10–13 µm, with droplets larger than 50 µm in diameter observed.

Small diurnal changes in drop-size spectra occur as a result of changes in cloud dynamics between night and day. Modeling of marine stratocumulus clouds by Considine (1997) demonstrated increases in MVD of a few microns in the afternoon and decreases at night, with minima in the morning. Much of the effect is due to daytime decreases in dry air entrainment and increases in entrainment at night.

An active area to watch for advances in information regarding drop-size spectra, outside of aircraft icing, is climate change research. Measurements and models characterizing cloud microphysical properties have become critical for parameterizing the effects of clouds on climate change. Radiative models used to simulate potential climate change and isolate the effects of greenhouse gases are very sensitive to cloud drop-size distribution (Choularton and Bower 1993, Telford 1996). Experiments analyzing the roles of cloud microphysical properties in climate change that are either in progress or completed include the Atlantic Stratocumulus Transition Experiment (ASTEX), the First ISCCP (International Satellite Cloud Climatology Project) regional experiment (FIRE), and the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) program.

The general characteristics of MVD by cloud genera are understood. However, less is generally understood about cloud drop size than about cloud liquid-water content. Controls of drop-size spectra are not well parameterized, although the general controls are believed to be understood. Changes in drop size over time within storms, and diurnally, have been tracked and simulated, but general theory explaining drop-size evolution over time is not mature.

Understanding of drop size has been hindered by the need for improved instrumentation, the three-dimensional complexity of liquid water within clouds, the need for observation flights focusing on drop-size measurements, and too much emphasis on reporting only MVDs instead of the full drop-size spectrum.

4.3.3 Supercooled large drops

The existence of large droplets (>50-µm diameter) was well known to early NACA investigators of the microphysics of icing clouds, but they were not included in the FAR 25, Appendix C tables, which include drop sizes from only 15 to 40 µm (FAA 1991). Sand et al. (1984) and Politovich (1989) state that droplets larger than 30 µm in diameter have a greater effect on flight than smaller droplets. Hansman (1985) indicates that, from model and wind-tunnel tests, large drops present a much larger threat to aircraft than small drops and that even a small liquid-water content in large drops may be a significant icing threat. Bragg (1996) attributes large-droplet ice accretions, and the formation of ice ridges aft of ice-protected areas, as a likely cause of flow separation, aileron snatch, and loss of roll control. Shah et al. (1998) indicate that secondary ice shapes producing ridges spanwise along a wing can be created by supercooled large drops (SLDs), even with a heated leading edge. The larger drops also strike unprotected areas of the aircraft, such as the underside of the wing, increasing drag (Politovich 1989). Loss of a research aircraft by the Desert Research Institute in icing conditions may have been caused by SLDs, typically drops in the 50- to 500-µm-diameter size range (Telford 1988). Coffey (1995) describes the hazard of SLDs as observed from the cockpit of a research aircraft, with advice on how to avoid and exit SLD conditions.

Droplets larger than about 50 µm in diameter do not remain suspended in clouds by turbulence effects as do smaller droplets. Gravitational forces cause them to fall at greater speeds as drop size increases, producing precipitation. Though long recognized as a hazard, these large drops have been receiving more attention in recent years. The crash of an ATR-72 at Roselawn, Indiana, in October 1994, focused the attention of aviation icing researchers on SLDs and their unique hazard to aircraft (NTSB 1996, Broderick 1996).

Early research reports describing the results of flights measuring the microphysical properties of icing clouds have mentioned supercooled drizzle drops, for example, Kline (1949), but relatively few reports focused on SLDs. Rodert (1951) and Lewis (1951) both indicated the importance of freezing drizzle and freezing rain as aircraft icing hazards. However, most work until recent years has been in response to needs to understand raindrop-formation mechanisms for cloud physicists, rather than for aviation needs (Fletcher 1962, Hobbs and Deepak 1981, Cotton and Anthes 1989, Rogers and Yau 1989, Houze 1993, Young 1993, Pruppacher and Klett 1997).

Isaac and Schemenauer (1979) found supercooled large drops near the tops of cumulus clouds near Yellowknife, NWT. Many cloud tops between 0°C and –8°C had concentrations of supercooled drops larger than 70 µm. About twice as many clouds had concentrations of large water droplets as had concentrations of ice crystals. Large drops were associated with low liquid-water contents, and droplets larger than 150 µm never had a concentration of more than 1 L^{-1}. The authors could not explain why the drops existed and did not relate them to aircraft icing since the purpose of the research was related to precipitation enhancement.

Politovich (1989) describes icing from large droplets on a research aircraft flying in California and Arizona. Eleven flights are characterized within a narrow temperature range, between –5.5 and –9.4°C and drop concentrations of generally less than 100 cm^{-3}. Conditions had the greatest effect on aircraft performance when fewer than 0.1 – 1 cm^{-3} droplets occurred in a size range from 30 to 400 µm. Politovich indicates that the frequency of these occurrences is low but not rare. Ample moisture and time, accompanied by lift, must be available to create these large drops. She suggests that environments most likely to experience SLDs are orographic and upslope in warm fronts and within the warm sector of cyclones where adequate moisture and lift are available.

Feingold et al. (1996) argue, from numerical simulations, that the production of drizzle within clouds is related to droplet residence time and within-cloud turbulence. Vigorously growing clouds produce more drizzle because they allow longer in-cloud drop dwell times, prolonging the collision–coalescence process. Their arguments are similar to that of Politovich (1989).

Hudson and Svensson (1995) measured drizzle-drop concentrations off the Southern California coast as part of the FIRE experiments and associated drizzle drops closely with lower drop concentrations, larger droplets overall, and a larger drop spectral width. They attribute the formation of drizzle drops in stratus clouds to areas where updraft velocities are greater, which causes different percentages of cloud condensation nuclei at the cloud base to be activated. They suggest that updraft velocity can be used to predict drop concentration and the width of the drop-size spectrum.

In one of the most ambitious drizzle measurement programs to date, Cober et al. (1995; 1996a,b,c) describe freezing drizzle measurements made in the Canadian Freezing Drizzle Experiment (CFDE) off the Newfoundland coast. Freezing drizzle was encountered in four research flights within thick (~1000-m) stratiform clouds. In these four encounters, liquid-water content varied between 0.05 and 0.2 g m^{-3} when MVDs were larger than 40 µm. MVDs as large as 950 µm were measured in freezing rain below the cloud base. Within clouds, MVDs often exceeded 500 µm. When combined liquid-water contents and MVDs were compared to FAR 25, Appendix C, 34 of 147 data points fell outside the envelopes. They conclude that freezing drizzle may be a frequent phenomenon in East Coast winter storms and a significant aviation hazard.

Jeck (1996) published the most comprehensive review to date of the state of knowledge about freezing rain (ZR) and drizzle (ZL) with regard to aviation. He indicates that few instrumented aircraft have flown in ZL and ZR, and that little is known about the meteorological conditions and geographic locations of SLD occurrence. Elevated ZL and ZR, encountered by aircraft in flight, are a hazard that may not be experienced at the surface if they freeze as sleet before reaching the ground. Though techniques have been proposed for detecting ZL and ZR from radiosondes, no reliable methods of prediction are available, especially for ZL, which can occur without the traditional warm layer often found in ZR. ZR and ZL are typically lower-altitude phenomena, with most occurring below 3811 m agl, making them a distinct hazard to nonpressurized aircraft, helicopters, and all aircraft on approach and departure. Little is known about the frequency, depth, and horizontal extent of ZR and ZL layers, the causes of ZL, and the full range of meteorological conditions associated with each. Jeck indicated that the use of MVD to characterize drop spectra associated with SLDs is not appropriate because the MVD provides no indication that SLDs exist.

Hobbs and Rangno (1996) observed supercooled drizzle drops with very high liquid-water contents off the Washington coast. The stratocumulus clouds were trapped above an inversion, preventing cloud condensation nuclei from the marine boundary layer below the inversion from reaching the clouds. As a result, drop concentrations were low (~ 500 L^{-1}), liquid-water contents were high (up to 0.8 g m^{-3}), and drops as large as 200 μm in diameter were present. The authors indicate that supercooled layer clouds that form in clean maritime air (lacking cloud condensation nuclei) that is decoupled from the surface could pose a significant threat to aircraft from supercooled drizzle or rain.

Cober et al. (1996b,c) report conditions off the east coast of Canada similar to those reported by Hobbs and Rangno (1996). Freezing drizzle was observed in 1100-m-thick stratiform clouds in temperatures between –11°C and –8°C. The maritime air was very clean, with condensation nuclei allowing only a few drops to grow large and coalesce. Though the MVD was 29 μm, cloud droplets larger than 40 μm exceeded 300 L^{-1}, and 500-μm-diameter drops were measured near the cloud tops. This suggests one mechanism for ZL, that of isolating humid air with few condensation nuclei, allowing coalescence and drop growth to occur.

In reports exploring the causes of ZL off the Canadian east coast, Isaac et al. (1996) and Cober et al. (1996b,c) review the processes that could cause ZL and compare them with CFDE measurements. In Newfoundland, ZL is associated with easterly and southeasterly winds and rarely with westerly winds. Only about 15% of ZR cases are nonclassical, but 60% of ZL cases are nonclassical. Classical ZR and ZL result from overrunning, such as occurs within warm fronts. Nonclassical drizzle formation does not involve overrunning. Mechanisms may include giant aerosol initiation of large drops, wind shear leading to entrainment, mixing and coalescence, long drop lifetimes in stratiform clouds that encourage drop growth, and high supersaturations. Eleven days of flights in both classical and nonclassical freezing precipitation situations showed no consistency of mechanism, except for wind direction and the existence of inversions and wind shear near the cloud top.

Climatologies of SLD accretions at the surface have been developed as a method of assessing where freezing rain may be occurring aloft as a hazard to aircraft. Strapp et al. (1996), Robbins and Cortinas (1996), and Bernstein and Brown (1997) completed independent climatologies of the frequency of SLD events in North America to assess where aircraft icing due to ZR and ZL may be occurring with greater frequency. All maps indicate freezing precipitation at the surface as being most common east of the Rocky Mountains, with frequency increasing from the mid-Mississippi Valley to the Northeast and Labrador, with an axis through the Great Lakes Basin. Ahmed and Brown (1995) produced a climatology of in-flight ZR globally, with seasonal detail in Great Britain and Europe from the U.K. Meteorological Office's numerical model output. Their model-derived climatology suggests high frequencies of ZR over the Atlantic and Pacific Oceans.

It is evident that SLDs create uniquely hazardous in-flight icing conditions, yet little is known about the phenomenon: its characteristics, its climatology, or what comprises an SLD condition (Shah et al. 1998). Flights during the winters of 1996–1997, 1997–1998, and 1998–1999 by NASA Glenn Research Center's Twin Otter aircraft into SLD should help answer some of the remaining questions (Miller et al. 1998). Jeck's (1996) report addresses most of the weaknesses in knowledge about SLDs and is probably the most complete and succinct paper on the subject from an aviation perspective.

4.3.4 Temperature

The thermal environment of an icing event determines the type, amount, and location of ice formation on an airframe (Cooper and Sand 1997). The thermal environment is controlled by radiative, convective, conductive, latent heat and advective processes of the atmosphere and the airframe and by the dynamics of the aircraft moving through the atmosphere. When isolated from the airframe and the thermodynamics of the icing processes, thermal processes within the atmosphere alone determine the temperature of air and of drops.

The "source" of cold also affects the amount, type, and shape of ice that forms. For example, droplets warmer than 0°C may freeze upon a cold-soaked airframe, but supercooled droplets may not freeze efficiently on an airframe warmed aerodynamically above freezing. Supercooled drops impinging upon an airframe that is colder than 0°C will typically produce ice. Of the thermal processes operating, the temperature of the droplets, or the temperature of the atmosphere surrounding the droplets, is typically most important in determining whether ice will form on an airframe.

According to Rodert (1951), it is tacitly assumed that cloud droplets are at the same temperature as the surrounding atmosphere. This may not always be true for cloud or for precipitation drops, which typically cool to the wet-bulb temperature of the surrounding atmosphere through evaporation (Cooper and Sand 1997). Since the relative humidity within icing clouds is typically near 100%, the dew point and air temperature will also be similar, especially within stratiform clouds of stable air masses. Within cumulus clouds with active updrafts and entrainment of dry air, evaporation and subsequent cooling may be greatest near the outside of the cloud where entrainment is most active (FAA 1991). Therefore, one will find warm cores in clouds with internal updrafts because of reduced evaporation and the release of latent heat as drops grow. In general, cloud-size droplets reach thermal equilibrium with surrounding air very rapidly, typically within 1 second (Borovikov et al. 1963). Precipitation drops cool to the wet-bulb temperature after they have fallen into dry air below cloud base and begin to evaporate, but lag times can be on the order of 10 s (Fletcher 1962).

Droplets may also be cooler than the surrounding air within warm tongues of air advected over colder surface air and below colder air aloft. Snow falling into these warm layers from above may partially or completely melt. However, until fully melted their temperature remains at 0°C, so they remain colder than the warm layer until all ice melts and the drops begin to heat through convection and radiation. These areas are often identified on radar displays as “bright bands”—zones where falling ice crystals melt and coalesce into raindrops.

Temperature within clouds may fluctuate several degrees over distances of only a few meters. In addition, within-cloud temperatures can be considerably different from outside-cloud temperatures. Rapid and significant temperature fluctuation from cloud to cloud, and within clouds, makes determination of supercooling difficult. For example, data from NCAR Winter Icing Storms Project (WISP) flights indicate that temperature fluctuations from clear air to cloud can be as much as 6°C (NCAR 1990). Flights in Poland with a rapid-response airborne thermometer show temperature fluctuations within clouds of 2°C in distances of less than 150 m (Haman and Malinowski 1996). Time series of temperature through the core of a warm cumulus cloud (Lawson and Cooper 1990) showed a 3 to 4°C increase of temperature upon entering the cloud, with similar subsequent cooling upon exit. Temperature within the cloud was nearly constant. Penetrations of supercooled stratiform clouds showed, depending upon the thermometer observed since several were being tested, a 0 to 1°C decrease in temperature when inside the cloud as compared with dry air around the cloud. In another case, but without identification of cloud genera, cooling of 3°C was observed within the cloud when compared with surrounding dry air. Lawson and Rodi (1992) penetrated warm cumulus humilis clouds with fast-response thermometers and showed immediate 6°C cooling when entering the clouds and immediate 6°C warming when exiting.

Temperature changes can also be large and rapid in the horizontal when an aircraft transits fronts, though not as rapid as upon entering or exiting clouds. For example, transiting a cold front in horizontal flight can produce temperature changes of 0.2°C per kilometer or more (Berry et al. 1945). Smaller changes are observed when transiting warm fronts in level flight. This is ignoring turbulent mixing in the shear zone along frontal surfaces, which can cause more rapid localized temperature changes.

The most rapid temperature changes, however, are experienced during ascent or descent rather than within level flight, so during approach and departure static outside air temperature (OAT) at the aircraft will not be a reliable indicator of air temperature within the flight path ahead of the aircraft. Vertical temperatures can vary, from nearly isothermal over large vertical distances to changing by tens of degrees over a few hundreds of meters, especially when transiting inversions. As an example, Schroeder (1990) illustrates a winter temperature inversion over the Denver area of about 22°C within a vertical distance of less than 500 m. Such rapid changes are not unusual during winter.

This evidence suggests that OAT measured at the aircraft, though a general indicator, is insufficient for determining if liquid water in the flight path is supercooled. Confidence in the representativeness of OAT to predict temperature ahead of the aircraft varies with the meteorological conditions around the aircraft and with the mode of flight: ascent, level, or descent.

Nonthermal parameters may be useful surrogates for indicating temperature. Detection of glaciation within a cloud suggests that any liquid water within the cloud is supercooled. However, if ice crystals are not present, the method is not effective because there is no physical indication of supercooling.

In addition to detecting temperature within the flight path, range-resolved temperature must also be sensed above and below the aircraft to provide a potential route of escape from icing into warm air. Since air temperature varies more rapidly vertically than horizontally, especially within inversions, sensing temperature above and below aircraft may be useful.

The accuracy of temperature measurement may also be critical because of its effect, with liquid-water content and drop size, on ice type, density, and shape on leading edges (Wright 1995). Since very small changes in temperature may create large changes in ice accretion amount and shape, it may be useful to measure temperature ahead, above, and below the aircraft with high accuracy.

4.3.5 Spatial structure

Spatial scales of icing conditions affect the utility of remote-sensing systems. Icing conditions that are spatially homogeneous over thousands of square kilometers offer less potential for avoidance without climbing or descending. The size of icing cells and storm areas also affects the needed sensing range of remote-sensing systems. Storms with small icing cells may be sensed by a remote-sensing system sufficiently to allow an aircraft to progress iteratively through the system. Storms with large icing cells may be too large to be sensed through, potentially trapping aviators (Fig. 2) (Kirkpatrick 1970). The inability to sense completely through icing reduces avoidance options and may limit an aircraft to turning back along its original route to avoid icing. Most icing areas may be scanned completely through with a detection range of 80 km or more, as suggested by Curry and Liu (1992).

Relatively little is known about the horizontal extent of icing conditions, though more is known today because of modern research flights than was known in 1979 when Milton Beheim of NASA Lewis Research Center indicated that the horizontal extent of the icing cloud had not been adequately defined (Beheim 1979). He also indicated that the fine-grain structure of the icing cloud had not been well defined.

FAR 25, Appendix C, tries to address icing spatial scale by providing tables for continuous conditions within stratiform clouds and intermittent conditions within cumulus clouds (FAA 1991). Jeck (1983) indicates, however, that the horizontal extent of icing specified in Appendix C has no specification for the discontinuity in icing and the size and frequency of any cloud gaps. He concludes that "horizontal extent," as indicated in Appendix C, does not imply the overall dimensions of icing cloud systems.

Jeck (1983) provides two methods of expressing the horizontal extent of icing. For engineering-design purposes, he indicates that the horizontal extent of icing encounters, consistent with Appendix C, is the "distance flown during a given icing encounter until a cloud gap of some specified duration signals the end" of the encounter. Of more use in determining the utility of remote sensing is the horizontal extent of individual icing events, where an icing event is the actual distance of icing, which ceases at a cloud gap of any length. Jeck reanalyzed NACA data by the horizontal extent of the icing event and presented modern data in the same way. The analyses indicate, as is consistent with Appendix C, that there is an inverse relationship between liquid-water content and event horizontal extent. Horizontal extent is about 33 km at a liquid-water content of about 0.01 g m^{-3} and is about 5.5 km for the largest observed liquid-water contents, about 1.5 g m^{-3}. This should not imply, however, that liquid-water content is constant for these distances. These are average values, and individual patches of larger or smaller liquid-water contents can occur within these extents. An aircraft with ice protection may be able to tolerate liquid-water content to a given magnitude but may have to avoid larger liquid-water contents. Thus, it may also be helpful to know the size of icing "patches" with larger than specified liquid-water contents.

The size of liquid-water content patches may be ascertained from measurements during research flights. In 1992, Cober et al. (1995) flew 31 missions, as part of the Canadian Atlantic Storms Project (CASP), into East Coast winter storms to measure cloud microphysical properties related to icing. The length of supercooled liquid-water content patches was measured. A patch was defined as having supercooled liquid-water content of at least 0.025 g m^{-3} for at least 0.5 km of flight. Patches terminated when supercooled liquid-water content was less than 0.025 g m^{-3} for 0.5 km. Average patch length was 4.3 km, with a mean liquid-water content of 0.13 g m^{-3}, and the median patch length was 1.7 km. About 90% of patches were less than 7 km in length, with less than 2% longer than 50 km. Flights were made in low-level stratus clouds and within low-pressure areas and through fronts.

Politovich (1982) describes flights through supercooled stratiform clouds over the Great Lakes and the Great Plains in 1981. A cloud extent started when the aircraft was within supercooled liquid cloud for at least 1 km, and cloud elements "separated by less than the element length were combined unless the gap was greater than 6 km." The average icing encounter in Great Lakes stratiform clouds was 9 km long, and within Great Plains stratiform clouds the average encounter was 24 km long. Embedded cells of supercooled liquid water within bands of frozen clouds averaged 6 km in length. The larger extents were a result of large-scale lifting of air masses. Though isolated pockets of higher liquid-water content occurred, the clouds were generally fairly uniform at a given flight level.

Cooper et al. (1982) characterized distances of liquid-water content encountered greater than specified thresholds, and the frequency and size of gaps between icing encounters (where evaporation or sublimation of ice accreted on an aircraft could occur). Data from 1083 flight hours in California, Montana, Utah, Florida, Kansas, Illinois, Michigan, and the Great Lakes in summer and winter conditions were used to compile the information. In all seasons, flights were in icing conditions, but at higher altitudes in summer than in winter. The flights deliberately sought the most severe icing conditions. Cooper and his colleagues present information indicating exposure distance in two ways:

- Probability of exceeding a given liquid-water content in a given distance
- Probability of exceeding a liquid-water content of 0.1 g m^{-3} for each region.

As examples, when averaged over 1 km, liquid-water content exceeding 0.1 g m^{-3} occurred about 5% of the time and exceeded 0.5 g m^{-3} about 1% of the time. When averaged over a distance of 10 km, liquid-water content exceeded 0.5 g m^{-3} about 0.5% of the time. Viewed regionally, there are large differences in the extent of liquid-water content greater than 0.1 g m^{-3}. The Great Lakes area, which has the lowest overall liquid-water content, has the longest continuous icing encounters, over 80 km in the winter. Kansas, Montana, Illinois, and Florida had short encounters, most being less than 36 km in length. In Kansas and Florida there was about a 1% chance that an icing encounter would extend more than 10 km. Cooper and his colleagues point out that only about 10% of encounters extended more than 5 km, and the majority of icing measured was in cumulus clouds.

Gap encounters are useful for assessing the utility of remote sensing to avoid icing, because aircraft could avoid ice by navigating gaps. Cooper et al. (1982) report that gaps are typically short, like icing encounters, with 50% being less than 5 km in extent. A gap occurred when liquid-water content was less than 0.01 g m^{-3}. Gerber (1996) reports liquid-water content gaps, or minima (called turbules), of a much smaller scale embedded within marine stratocumulus clouds. Turbules are typically a few hundred meters or less across.

Kline and Walker (1951) related icing to synoptic patterns in stratiform clouds during 22 flights from 1948 through 1950. In extratropical cyclones, most icing was associated with post-cold-frontal situations, with most icing in the southwestern and northwestern quadrants of the storm. Very little icing was found in the overrunning portions of warm fronts east of the storm center. Most icing was typically 300–400 km behind cold fronts, and north of the center of lows, similar to patterns reported by Ryerson (1990) at Mt. Washington, N.H., and Mt. Mansfield, Vt. These patterns are contrary to analyses of pilot reports of icing reported by Politovich* that indicate that most icing is ahead of warm fronts and near the center of lows, with least icing behind warm fronts and cold fronts.

Little is known about the horizontal extent of ZL and ZR, according to Jeck (1996) in a summary of knowledge about the phenomenon. Bennett's (1959) report indicated that most freezing rain occurs in overrunning situations, so it is associated with warm fronts in many instances. Freezing rain can extend continuously or intermittently several hundred kilometers parallel to a front and short distances perpendicular to fronts. It can also be associated with cold fronts, but then it typically is of shorter extent than in warm fronts. Design values use 160 km as a representative extent. There is no information for the extent of ZL, according to Jeck, who argues that extent should be related to the time an aircraft must spend below 7000 ft, especially on approach and departure. This agrees with Perkins' (1952) conclusions that over 50% of icing conditions in general are found during climb or descent.

* Personal communication, M. Politovich, National Center for Atmospheric Research, Boulder, Colorado, 1997.

Strapp et al. (1996) and Bernstein and Brown (1997) have created modern climatologies of the occurrence of freezing precipitation. Neither study, however, speculates about the spatial extent of individual freezing precipitation storms. Bernstein (1996) indicates implicitly that freezing precipitation does occur for hundreds of kilometers, but broken in continuity. As an example, he presents a map for 1800 hr on 6 March 1996, illustrating freezing precipitation as extending in a broken band from New York City through Missouri, with a maximum width of about 250 km.

In general, spatial patterns of icing on sub-kilometer to tens-of-kilometers scales, and icing's relationship to synoptic and mesoscale weather, are only generally understood. The ability to avoid icing is a function of its spatial distribution. Large cloud masses that are homogeneous with respect to icing are difficult to avoid.

4.3.6 Mixed-phase clouds

Supercooled liquid water freezes on aircraft structures, whereas ice crystals within clouds, snow, and ice pellets typically do not adhere (Riley 1998). Nevertheless, clouds composed of mixtures of ice crystals and supercooled water are of interest for remote sensing of icing potential for several reasons. First, remote-sensing systems scanning clouds that are completely glaciated or mixed phase must distinguish successfully between ice and supercooled liquid water and not be compromised by the presence of ice crystals. A remote-sensing system must be capable of quantifying the amount of supercooled liquid water mixed with ice crystals or of sensing beyond a frozen cloud in the foreground, for example, to a more distant supercooled liquid cloud.

The second concern for mixed-phase clouds is in reference to the need to range-resolve temperature to determine if sensed liquid water is supercooled. A cloud made up of a mixture of liquid water and ice crystals is likely to contain supercooled liquid water. As a result, even if a method is not found for range-resolving temperature, it may be possible to determine whether liquid water is supercooled by sensing the presence of ice crystals mixed with the liquid water. Thus, mixed-phase clouds may serve as a surrogate for explicit temperature measurement ahead of the aircraft. Mixed-phase clouds, however, may be less of an icing hazard than supercooled clouds without ice crystals (Guttman and Jeck 1987, Riley 1998).

Simply seeking ice crystals may not be a reliable solution to determining supercooling, however. Clouds may be composed completely of supercooled liquid water and still contain no ice crystals, or they may contain a concentration of ice crystals that is so small as to be not detectable. The success of using mixed-phase clouds as an indicator of supercooling is thus dependent upon the probability of supercooled liquid clouds containing detectable ice crystals. Parameterizing nucleation of water droplets in clouds, and the glaciation process, is one of the classical problems cloud physics has yet to solve.

When a cloud is cooled below 0°C, ice crystals could form. However, because there are relatively few ice nuclei in the atmosphere when compared with condensation nuclei, nucleation often does not begin until droplets cool to –10°C (Rogers and Yau 1989). Observations of 258 clouds by Hobbs et al. (1974, as cited by Rogers and Yau 1989) showed that glaciation typically does not begin until cloud-top temperatures cool to about –4°C, after which the percentage of clouds containing ice increases to 100% at a cloud-top temperature of about –20°C. Rogers and Yau (1989) state that it is impossible to determine at what cloud-top temperature any individual cloud will begin to glaciate or to estimate how much glaciation will occur. Thus, in general, clouds with tops warmer than about –5°C are ice free, and clouds with tops colder than –20°C are virtually guaranteed to have ice crystals (Riley 1998).

The first crystals to appear in a cloud must form on ice nuclei (Rogers and Yau 1989). Additional crystals are formed from secondary processes such as the fracture of ice crystals and the shattering or splintering of drops as they freeze. These crystal fragments then strike liquid-water droplets, causing them to freeze though contact nucleation, or the fragments simply serve as deposition nuclei (Houze 1993).

Overall, glaciation is difficult to predict because it depends upon cloud type, cloud age, liquid-water content, and geographical location—especially as related to air mass type and availability of icing nuclei (Rogers and Yau 1989). Since the probability of glaciation increases with decreasing temperature, it would be expected to find a monotonically increasing percentage of cloud water to be frozen at lower temperatures. This does not appear to occur, however. Instead, once clouds begin to glaciate, freezing occurs rapidly, and the final ice particle concentration is not proportional to temperature (Pruppacher and Klett 1997).

Mixed-phase clouds are also not necessarily uniformly glaciated. On the basis of a large number of soundings of nimbostratus clouds in Russia, Borovikov et al. (1963) report that three different types of mixed cloud structure can occur: clouds can consist of relatively uniform mixtures of crystals and water throughout, successive layers of water droplets and ice crystals, or three or four layers of warm water, supercooled water, mixed conditions, and ice. The relative frequency of each was observed 52%, 28%, and 20% of the time, respectively, in Russia.

Additional information about the utility of using mixed-phase clouds for indications of supercooling is available from various field programs. Tremblay et al. (1996) observed mixed-phase clouds at 4461 points as part of CFDE in 1995 off the Newfoundland coast. Plots of the proportion of liquid water vs. ice water within mixed-phase clouds showed a temperature dependence between 0°C and –10°C if liquid-water contents larger than 0.3 g m^{-3} are ignored. As temperature decreased, the proportion of ice increased. However, the relationship is also proportional to the cloud liquid-water content, with the proportion of cloud water nucleating increasing, at a given temperature, with cloud total liquid-water content. In flights through summer cumulus in southern Missouri, Koenig (1963) found glaciation related to drop size, with clouds with large drops rapidly forming high concentrations of ice crystals regardless of the availability of ice nuclei.

Bower et al. (1996) surveyed frontal and maritime convective clouds from the United Kingdom and continental convective clouds from New Mexico and Montana to refine parameterization schemes for global circulation models. Detailed analyses were done for all clouds that had been measured for glaciation activity using aircraft-mounted instrumentation. Continental and maritime frontal clouds had very rapid glaciation, beginning at 0°C, with total glaciation typically ocurring at temperatures of –10 to –15°C. Continental and maritime convective cloud glaciation was much slower and less complete, with glaciation beginning at 0°C, but at –3°C, typical clouds were only about 40% glaciated. At –15°C, some clouds were still 90% supercooled liquid water.

It is not clear from these studies whether glaciation begins in earnest at 0°C. Characteristics of mixed-phase clouds must be better defined to determine the probability of ice crystals at temperatures below 0°C. The most current and thorough review of mixed-phase clouds and aircraft icing is by Riley (1998).

4.4 In-situ instrumentation

In-situ measurements of cloud microphysics are needed to support and augment the remote sensing of in-flight icing conditions, and in-situ instrumentation is needed for improved characterization of icing cloud microphysics. Drop-size distributions are often not correctly represented by current measurement methods, and ice crystals and drops can be confused by the coarseness of sensing systems. Two measurements by the same model of instrument often do not agree when used on the same aircraft, which indicates repeatability or calibration problems. The dynamic range and sensitivity of instruments is often insufficient, and gaps in size distributions synthesized from combinations of instruments often occur.

In-situ instrumentation would be useful onboard all aircraft for sensing when icing conditions have been entered and for near-real-time calibration of onboard remote sensors. Instrumentation intended for use on all aircraft may not require the accuracy of research instruments. Ease of use, maintenance, cost, and size are more important factors in these applications.

Most current aircraft-mounted instrumentation suited for cloud microphysical measurements is intended for research applications. Very few instruments, notably air-temperature measurement devices, are sufficiently inexpensive and robust for general field use. The following is a brief review of available instrumentation and their general applicability. This review does not discuss instrumentation for detecting ice on aircraft surfaces, either preflight or in-flight. A review of in-flight ice detectors is available in the *FAA Aircraft Icing Handbook* (FAA 1991) and in an SAE document (SAE 1995).

Cloud microphysics measurement instruments are typically designed to measure temperature, liquid-water content, and elements of the drop-size spectrum. Early instrumentation was manually operated, but most modern instruments are electronic.

4.4.1 Temperature measurement

Temperature cannot be measured with a standard outside air-temperature probe because, in addition to accuracy and exposure problems, it is wetted by cloud water. A wet thermometer measures the wet-bulb temperature. Lawson and Cooper (1990) provide a detailed analysis of the problem. Thus, the most important task is to protect the thermometer from cloud droplets without disturbing the measurement.

A common temperature measurement instrument is the Rosemount total temperature probe (Haman et al. 1997). It is used by the U.S. Air Force (Glass and Grantham 1981), by NCAR (Sand et al. 1984) on its King Air, and on the Canadian Convair (Cober et al. 1996b). The instrument measures the resistance of a platinum wire in a bridge circuit. Accuracy is claimed to be from 0.5°C (Sand at al. 1984) to ±1°C (Cober et al. 1996b), but wetting in clouds is a problem.

NCAR and the AES also use reverse-flow temperature probes. According to Cober et al. (1996b), they are as accurate as the Rosemount and prevent wetting of the probe.

There has been considerable effort to improve the accuracy, resolution, and response time of thermometers to measure small-scale cloud features. Lawson and Cooper (1990) analyzed the Ophir radiometric thermometer to improve reliability within clouds and to improve response time. However, the sample volume is quite large (10 m in depth), and the instrument is large, expensive, and complex. The Ophir thermometer and the reverse-flow thermometer were both accurate within clouds, and the Rosemount was not (Lawson and Cooper 1990).

Marillier et al. (1991) constructed an ultrasonic thermometer that measured temperature ahead of an aircraft to avoid cloud-wetting effects and to obtain temperature at 100 Hz. Measurements were typically accurate to within a few tenths of a degree Celsius of a colocated Rosemount probe.

Lawson and Rodi (1992), Friehe and Khelif (1993), and Haman and Malinowski (1996) have constructed very fast response thermometers in an attempt to match the response time of a forward-scattering spectrometer probe (FSSP). These thermometers are very delicate, with either platinum wires 12.5 µm in diameter (Lawson and Rodi 1992), tungsten wires 2.5 µm in diameter, or small thermistors (Friehe and Khelif 1993, Haman and Malinowski 1996). Both wire probes are accurate but delicate and broke easily when stressed by high-speed airflow and precipitation. All three instruments are too delicate for general operational use, and the thermistor instrument had calibration difficulties.

4.4.2 Liquid-water content measurement

The first common instrument for liquid-water measurement was the rotating multicylinder, developed at Mt. Washington Observatory between 1940 and 1945 (Lewis et al. 1947, 1953; FAA 1991; Howe 1991). In the 1930s, a single rotating cylinder was used. The rotating multicylinder, still in use at Mt. Washington Observatory but no longer used on aircraft, is used to determine cloud liquid-water content and the shape of the drop-size spectrum. The multicylinder typically consists of six cylinders, stepped in diameter. The shape of the drop-size spectrum is determined by comparing the mass of ice on each cylinder to curves of expected ice accretion on each cylinder for a given shaped drop spectrum, after theory developed by Langmuir and Blodgett (1946). Cloud liquid-water content is related to the mass of ice on the cylinder; the smallest cylinder with the highest collection efficiency is typically used for the calculation.

Rotating multicylinders are manually operated and, depending upon cloud liquid-water content and relative wind speed, are exposed from a few minutes to more than 20 minutes (Kline 1949, Howe 1991). Jeck (1980) thoroughly reviews problems with the multicylinder method, especially with regard to runoff near the Ludlum limit. The advantage of the multicylinder method is that, with a skilled operator, it is cheap, easy to use, and reasonably accurate in colder temperatures, smaller drop sizes, and moderate liquid-water contents.

The only other early method of measuring liquid-water content that received much use was the icing-rate meter, a horizontal rod with holes facing into the relative wind (Perkins 1952). Ice plugging the holes would be sensed with a pressure transducer, triggering a deicing cycle. Assumptions about ice density and the meter's collection efficiency allowed rough estimation of liquid-water content. Electronic devices have since replaced multicylinders.

Today, the primary electronic devices for measuring liquid-water content are the Rosemount ice detector and the King and Johnson–Williams hot wire probes (FAA 1991, Knollenberg 1981, Glass and Grantham 1981). The Rosemount ice detector is a standard instrument on most icing research aircraft and on the ground, and it may also be used to compute liquid-water content by relating the deicing rate of the detector to relative wind velocity (Brown 1981, FAA 1991, Claffey et al. 1995). A 6-mm-diameter by 25-mm-long probe vibrates axially at its resonant frequency of 40,000 Hz. As ice accretes on the probe, its frequency drops until, at a preset frequency, a heater deices the probe. Liquid water may be computed if the mass of ice, the exposure time, the relative wind velocity, and the collection efficiency of the probe are known. The detector is reasonably accurate, within the range of conditions found in most mountain and aircraft applications, at moderate liquid-water contents (Claffey et al. 1995). The typical liquid-water performance range is 0.05 to 3.0 g m^{-3} (FAA 1991).

The Johnson–Williams probe exposes a hot wire to the droplet-laden air flow, and a second "compensating" wire is protected from liquid water but exposed to the air flow (Knollenberg 1981, FAA 1991). The second wire compensates for variations in air speed, altitude, and air temperature. The resistance of the wires changes as they warm and cool, and the change of resistance is measured through a Wheatstone Bridge circuit. The instrument has an absolute liquid-water range from 0.0 to 1.5 g m^{-3} (Jeck 1980) to 6.0 g m^{-3} (FAA 1991). Personne et al. (1982) found undermeasurement of liquid-water content in large-drop environments for that portion of the liquid-water content in droplets larger than 30 mm in diameter. A ±20% error limit is often assumed for the probe, but it can be smaller with wind-tunnel calibration (Baumgardner 1983, Sand et al. 1984).

The CSIRO, or King, hot-wire probe measures liquid water by maintaining a copper wire coil nominally 1.5 mm in diameter exposed to the air stream at a constant temperature (King et al. 1978, Knollenberg 1981, FAA 1991). The electrical energy necessary to maintain a constant temperature under the cooling influence of the air stream and impinging water droplets is related to liquid-water content after corrections are made for air temperature and wind speed. The probe requires no wind-tunnel calibration, is rugged, and is easily field serviced. King et al. (1978) reported a sensitivity of 0.02 g m^{-3}, a response time better than 0.05 s, and an accuracy of 5% at 1.0 g m^{-3}. Baumgardner (1983) could draw no conclusions about the King probe, other than that it was promising and deserved more study. Cober et al. (1996b) use the King probe on the Canadian Convair and claim accuracies of ±0.02 g m^{-3} for liquid-water contents of less than 0.2 g m^{-3}. In a range of liquid-water contents between 0.1 and 1.25 g m^{-3}, and with MVDs between 10 and 40 µm, Ide (1996) found accuracy for the King probe to be within ±0.1 g m^{-3} of the calibrated NASA Glenn Research Center Icing Research Tunnel (IRT). In general, wind-tunnel testing has shown the King probe to be generally accurate to 5% at 1.0 g m^{-3}, and it is generally superior to but more fragile than the Johnson–Williams probe (FAA 1991).

Another hot-wire-based instrument is the Nezorov probe developed in Russia (Korolev et al. 1996). Currently being flown on the Canadian NRC Convair and the NASA Glenn Research Center Twin Otter, it has the unique ability to quantify both the supercooled liquid-water content and the ice-water component of clouds (Miller et al. 1998). Similarly to the Johnson–Williams probe, a reference heater corrects for convective heat losses. Though details are not available, it appears that liquid- and ice-water components are separated by the lag caused by phase changes as water vaporizes within the instrument (but ice particles may break away, causing negligible heat loss—and error). The exact process is not clear. Comparisons with the King probe in CFDE flights show less than 10% disagreement, with the Nezorov showing better performance in SLD environments. Wind-tunnel tests demonstrated better stability than the King probe at low temperatures and the ability to measure the frozen component of mixed-phase clouds. Verification in snow has not been possible because of a lack of standards.

Liquid-water content may also be measured optically, typically utilizing the interaction of laser-based collimated light and droplets. Gerber (1991, 1996) has developed an instrument, the particle volume monitor (PVM), that measures cloud liquid-water content, integrated particle surface area, and effective cloud droplet radius. All measurements are made simultaneously in a large, 1.25-cm^3 sample volume. The instrument operates by passing droplets through a laser beam, which then forward-scatter laser light through a lens and a variable transmission filter onto a detector. Output from the detector is mathematically inverted to derive liquid-water content and effective drop radius. The instrument resembles a class of instruments called "laser-diffraction particle-sizing instruments" (Gerber 1996). Comparisons of the PVM with other instruments in environmental chambers, on mountain tops, and on aircraft have been encouraging. The instrument has been demonstrated to be reliable in large-drop environments and in large liquid-water contents. It also does not appear to be disturbed by ice crystals, but independent tests must be done before the full accuracy and reliability of the instrument is known.

The forward-scattering spectrometer probe (FSSP), developed by Knollenberg (1981) and manufactured by Particle Measuring Systems (PMS), is the most commonly used optical probe; it is found on nearly all research aircraft (Sand et al. 1984, Cober et al. 1996b, Baumgardner et al. 1993, Thomas and Marwitz 1995). Intended for measuring drop sizes from 2 to 47 µm in diameter (94 µm in extended mode), cloud liquid-water content can be computed by integrating the spectrum of drop sizes. However, liquid-water measurements are prone to large error due to over- or undersizing of drop sizes. The instrument operates by forward-scattering light through cloud droplets as they pass through a narrow laser beam to a detector that records a drop size proportional to the flash of light. Drops are classified into fifteen 3-µm-wide bins. Sources of error in the instrument are a small sample volume, false sizes from ice crystals, ice accretion and fogging of the optics, blockage of airflow through the instrument by ice, and saturation of the instrument's electronics at high airspeeds and large particle concentrations (FAA 1991). In addition, large drops are typically incorrectly measured. As a result of drop-size measurement errors, liquid-water contents typically have up to 34% error (FAA 1991, Baumgardner 1983). Ide (1996) found liquid-water contents computed from an FSSP to be overestimated by 50% in MVDs up to 60 µm, and by 100 to 150% in larger MVDs at NASA's Glenn Research Center Icing Research Tunnel. Baumgardner et al. (1993) and Brenguier (1993), however, have successfully modified the FSSP to measure the microstructure of clouds at the centimeter scale.

The Phase Doppler Particle Analyzer (PDPA), developed by Aerometrics, Inc. with assistance from NASA Glenn Research Center (NASA 1997), measures drop diameters from 0.7 to 125 µm but can be extended to 2000 µm (Aerometrics 1997). Droplet sampling is made in a small sample volume at the intersection of two laser beams. Droplets passing through the beams create an interference fringe pattern that is projected into several detectors. The detectors produce a Doppler signal proportional to the droplet's velocity and size. Droplet number density, and thus liquid-water content, are also computed. Calibration is not necessary. Models of the instrument have been developed for both wind-tunnel and aircraft use. However, the PDPA typically does not appear on equipment lists of primary cloud research aircraft.

4.4.3 Drop-size measurement

Measurement of cloud drop-size spectra has been important since early aircraft icing research, primarily because of their impact on ice shape, ice type, collection efficiency, and runback. However, the increased interest in SLDs in recent years has placed renewed emphasis on drop-size measurement. Fewer instruments are available for measuring drop-size spectra than for measuring liquid-water content, but many of the instruments described above for measuring liquid-water content have dual uses and measure both. In the case of optical instruments, liquid-water content is typically derived from the measured drop-size spectrum and drop concentration.

Except for oiled or soot-covered slides, the rotating multicylinder described earlier was the first widely used instrument for obtaining the shape of the drop-size spectrum and MVD (Lewis et al. 1947, 1953; FAA 1991; Howe 1991). The drop-size spectrum shape is determined by, in effect, fitting the accreted ice weights of the six cylinders to a series of curves, each representing a different droplet spectrum shape. The rotating multicylinder method provides only a general indication of the breadth of the droplet size distribution, in part because it can be fit to only a finite set of curves and because some clouds have bimodal or multimodal distributions. Howe (1991) states that accuracy in determination of liquid-water content and droplet size is better than ±10% when cloud drop-size distributions are narrow or moderately broad. When drop-size distributions are extremely broad, accuracy is reduced to about ±20%.

Gerber's PVM (1991, 1996; Gerber et al. 1994) provides the effective drop radius of clouds. Few comparisons have been made with other instruments, but a comparison with the FSSP (Gerber 1996) shows a linear relationship between the two instruments, though not a 1:1 relationship. Gerber suggested that the mismatch, with the FSSP providing smaller drop sizes than the PVM, was due to errors in the FSSP.

The FSSP was described in the liquid-water discussion above, where some if its problems of measuring drop size were also discussed. Overall, the instrument tends to broaden the drop-size spectra and, in drops larger than about 45 µm, measurements may not be trustworthy (FAA 1991).

Optical array probes (OAPs), manufactured by Particle Measuring Systems (PMS), measure drop size by imaging (Knollenberg 1981, Oldenburg and Ide 1990a, FAA 1991). OAPs image droplet shadows onto an array of photodiodes by allowing drops to flow through a laser beam. The loss of light on an individual array element is detected by a logic circuit that measures the shadow size. The drop size is a function of the shadow size and the optical elements between the drop and the detector array. If the measurement is made along one dimension of the particle, the probe is called a 1-D probe. Only shadows fully within the array are accepted, so large droplets—droplets not fully within the array—are rejected. The range of drop sizes measured is typically 20 to 300 μm, or 300 to 4500 μm; and other ranges are available (Knollenberg 1981, FAA 1991).

OAP 2-D probes are similar to 1-D probes optically, but enhanced signal processing speed allows the photodiode array to be scanned faster, retrieving, in effect, a shadow of particles as they traverse the laser beam. The result is an image of particles indicating the shape of ice crystals and the size of drops. Particle sizes are binned into 64 size classes. Two-D probes have been configured to detect particles up to 6400 μm in diameter (Marcotte et al. 1996). The accuracy of OAPs has been scrutinized in recent years with the renewed interest in SLDs. Problems of aircraft speed and location of the drop within the imager depth of field can cause OAPs to miss smaller drops and oversize large drops (Lawson et al. 1996, Morrison et al. 1997). These problems are detected when FSSP and OAP ranges overlap and when OAPs are compared with other instruments. New array-processing techniques and algorithms have been suggested to correct these problems (Hobbs et al. 1996, Korolev et al. 1996).

A comparison of the PDPA with the FSSP and a PMS OAP (Oldenburg and Ide 1990a,b) indicates that all three instruments generally agree well. Disagreements occurred in drop sizes smaller than about 10 μm because smaller droplets were suspected of freezing, and each instrument treats ice crystals differently because of the differing technologies, causing mismatched sample statistics. They also disagreed for MVDs larger than 30 μm because of the configuration of the PDPA, which could be reconfigured to detect larger drop sizes. The PDPA has the advantage of being a smaller instrument than the PMS probes, and it has the capacity of sensing a wide range of drop sizes with one instrument, whereas the PMS probes require two instruments, the FSSP and an OAP.

Lawson et al. (1996, 1998) and Lawson and Cormack (1995) describe new optical probes that solve problems with the FSSP and OAPs. The new instruments, which are in near-production stage for both ground and airborne use, are the cloud particle imager (CPI) and the cloud droplet spectrometer (CDS). The CPI creates images of cloud particles at a rate of 30 s^{-1}, but at a potential rate of 240 s^{-1}. Image detail as small as 2 μm is possible, with maximum possible size limited by sample volume. Shadowgraph-type images of ice crystals can be made of nearly photographic quality. Images can be obtained in real-time, and techniques are in development for retrieving liquid-water content and drop-size spectra.* The second instrument, the CDS, measures the angular resolution of forward-scattered light from an ensemble of cloud drops. A 256-photodiode array measures the scattered light, and liquid-water content is computed from the angular measurements of the forward-scattered light, which expresses the collective drop sizes of the drop ensemble. Liquid-water content measurements have been successfully compared with other instruments in a wind tunnel, and drop-size spectra measurements have been tested in the laboratory, aboard an aircraft, and at Mt. Washington Observatory. No data have been published in the open literature demonstrating the CDS's ability to measure liquid water or the drop-size spectrum.

4.5 Terminology

A remote-sensing system designed to detect and map icing potential within a projected flight path will sense the meteorological conditions that create ice on an aircraft: liquid-water content, temperature, and drop size. Then the remote-sensing system may utilize expert system or fuzzy logic to create information for a cockpit display that the pilot can use if icing is entered. Since ice cannot occur on the aircraft until the aircraft enters the icing conditions, only an explicit numerical model operated with the remote-sensing system, a set of guidelines that relate icing potential to expected performance, would solve the problem of how to relate meteorological conditions to the pilot. Bragg et al. (1998) propose a smart icing system that recognizes how aircraft systems should respond to icing and advises the pilot after the aircraft has entered icing. A similar system could be activated before an aircraft enters icing and act in response to remotely sensed icing conditions ahead of the aircraft.

Current terminology used to categorize or classify icing intensity, or severity, is often inconsistent among government agencies, difficult to interpret and, at times, contradictory (Erickson et al. 1996; Green 1995; Auld 1989; Newton 1977, 1979). Currently, the National Weather Service defines icing intensity with descriptions that are related only to aircraft and contain no meteorological criteria (Auld 1989, Newton 1979). According to Newton (1979), NWS definitions of trace, light, moderate, and severe are only reporting definitions and contain no meteorological information that can be used to forecast icing.

Newton (1979) also indicates that the National Weather Service definitions are not related to FAA icing regulations (FAA 1991). Uniformly understood icing

* Personal communication, R. Paul Lawson, Stratton Park Engineering Corp., 1999.

definitions are needed that are defined in standard terms (Auld 1989, Newton 1979). A graduated, parametric method of describing icing severity should be developed that is meaningful to meteorologists, aircraft designers, regulators, and operators (Erickson et al. 1996).

A remote-sensing system must, at minimum, supply information to the pilot with regard to the icing potential of a given volume of atmosphere in the flight path. A cockpit display must relay to the pilot information that enables a risk-management decision to be made. This means the display must either provide information that is uniformly applicable to all aircraft, but to which the pilot can reference his aircraft, or the system must directly indicate the hazard potential to that particular aircraft. According to Newton (1977, 1979), the most tenable solution with current definitions is to use a form of the old NACA icing intensity curves. The FAA is addressing terminology problems as part of the FAA Inflight Aircraft Icing Plan (FAA 1997).

5.0 TECHNOLOGY DEVELOPMENT

5.1 Summary

A remote-sensing system, operated either from the ground or from an aircraft, must sense the three-dimensional fluctuation of atmospheric liquid-water content, drop size, and temperature both from outside of icing conditions and from within icing conditions. In addition, the sensing system must have a range, resolution, and refresh rate sufficient to satisfy pilot needs. The capabilities of different technologies are often vastly different, depending upon whether scanning is toward space, toward the earth's surface, or in the horizontal plane ahead of an aircraft. In addition, it is likely that no single sensing technology is capable of providing all sensing needs—a fusion of technologies will be necessary.

Radar is the most viable technology for providing range-resolved cloud liquid-water content through large expanses of cloud. Its scan rate is rapid, orientation is generally not a limitation (unless observing below the horizon where earth reflections may be a problem), and there are a variety of bands from which to choose. Radar is a reasonably mature technology, and its basic backscatter capabilities may be augmented by Doppler and polarization techniques.

An important issue that must be addressed in the use of radar for remotely detecting icing conditions is to develop accurate and robust techniques for retrieving liquid water, drop size, and temperature information from radar backscatter. Developments in this area include the differential attenuation method of liquid-water retrieval demonstrated by NOAA-ETL (Martner et al. 1991; 1993a,b) and the neural net retrieval of liquid water and drop size by Quadrant Engineering (Mead et al. 1998). More work is needed to perfect existing information-retrieval methods and to make them more robust. Doppler and polarimetry techniques may be able to provide information about drop-size distributions. Most cloud microphysical work occurs in the X, K_a, and W bands, most ground-based precipitation measurement occurs in the S and C bands, and in X band from aircraft. A detailed sensitivity analysis is needed to find the optimal mix of requirements for detecting liquid-water content and drop-size information from ground-based and airborne systems.

Radar has shown modest success at measuring atmospheric precipitation and cloud water content—both liquid and frozen. Rainfall rates may be estimated with S- and C-band radars. NWS NEXRAD radars are an example of a system with some rainfall rate capabilities that may be useful for detecting freezing rain and perhaps freezing drizzle conditions around airports. Although not practical on aircraft because of size, using S band to detect freezing precipitation, X- and K_a-band differential attenuation techniques to detect cloud water, or multiband X-, K_a- and W-band neural network techniques may be optimal combinations at airports. In addition, Doppler and polarization techniques may provide some indication of the drop-size spectra and the presence of ice crystals.

A possible problem of radar, especially of the differential attenuation methods using two or more wavelengths, is the need to know droplet temperature to extract an accurate liquid-water content measurement because of the dependency of backscatter on drop temperature (Rinehart 1997). In addition, in military applications radar could place an aircraft that is sensing icing conditions at tactical disadvantage. Radars with stealth-like capabilities should be investigated.

In general, for ground-based systems, the focus should be on S- or C-band systems for determination of precipitation rate and precipitation liquid-water content estimations and on X, K_a, and W bands for determination of cloud water content. Doppler and polarization techniques are available and practical in ground-based systems, but for airborne systems they may not be useful. For general aviation aircraft, (relatively) inexpensive K_a- or W-band radar could be used to simply indicate the location of cloud bases and tops if pointed to zenith and nadir—a useful tool to escape icing.

Microwave radiometry has the potential to remotely sense icing conditions and, like radar, has been proposed and used for several icing studies. Microwave radiometers are capable of integrating or profiling liquid-water content and water vapor and profiling temperature. These capabilities have been demonstrated for zenith and intermediate angles.

There are several ways radiometers could be used to detect icing conditions. Ground-based airport systems could use scanning radiometers to measure liquid water and temperature profiles with height. Integrated water could be distributed through the atmosphere to determine volumetric cloud water content if combined with cloud base, top, and layer information from a K_a radar. However, this can now be accomplished without radar by the Radiometrics profiling radiometer. The ability of radiometry to scan liquid water at airports is nearly a mature technology, with the greatest concerns being the need to keep sensors free of moisture and improving scanning rates. Long scan time is one of the most serious radiometer problems because they are passive devices. At airports, this can be overcome by using multiple radiometers, each assigned to a different sector of sky, but it is a greater problem for airborne systems.

Airborne radiometry of cloud liquid water does not appear to have been tried from aircraft. It is theoretically possible for airborne radiometers to measure integrated liquid water scanning in the horizontal, and that feasibility is being analyzed using measurements made from the summit of Mt. Washington at the Mt. Washington Icing Sensors Project (MWISP). However, it may be more feasible at 85 GHz than at the more commonly used 37 GHz because of greater sensitivity to cloud water at 85 GHz. This needs to be explored.

As an alternative to horizontal scanning, or in addition to it, radiometers might be able to sense vertically, at zenith and at nadir, from an aircraft, as is now done from the ground and from satellites, respectively. The amount of liquid water above and below the aircraft could then be determined, and radar might be used to simply determine cloud tops and bases. The slow integration time of radiometers, however—many seconds—would provide only an averaged or integrated liquid-water content. This may be useful information, especially in level flight within relatively uniform clouds, but during climb-out and descent, and within fluctuating clouds such as cumuliform, this technique may not be as useful because of the long integration times and limited spatial resolution of microwave radiometers. In addition, nadir-viewing aircraft radiometers would have the complexity of radiation from the earth's surface, and varying altitude above the surface, making cloud-water retrieval more difficult. This suggests that although ground- and satellite-based radiometers may be able to measure integrated liquid water successfully now, airborne systems are presented with greater difficulties that will require more retrieval technique modeling and fieldwork. In addition, there is no indication that radiometers can detect characteristics of the drop-size spectra or detect ice, though it has been theorized that drizzle-size drops may be identified by polarization effects.

Lidar, especially multiple-field-of-view techniques, has promise for measuring cloud liquid-water content and some aspects of the drop-size spectra and cloud phase composition using polarization. However, lidar's inherent liability, its inability to penetrate cloud of large optical depth more than a few hundred meters, is severe. Lidar may be a useful, inexpensive technique for allowing aircraft, especially those flying night VFR (visual flight rules), to avoid icing, but it cannot provide guidance to escape icing. Its potentially low cost, high scan-rate capability, and small size may make it a practical tool for small helicopters and light aircraft, especially aircraft operating in the Far North with no ice protection in often limiting weather and few winter hours of daylight. Development along these directions is being made in Canada. Canadian needs for this VFR cloud and icing avoidance capability may be great in the northern territories.

Temperature measurement is needed to determine if cloud water or liquid precipitation is supercooled. It is also needed for radar retrieval of cloud water content.

Two mature technologies are available for sounding temperature from the ground: RASS (radio acoustic sounding systems) and microwave radiometers. RASS provides greater temperature resolution and thus accuracy, which is especially needed during the winter when inversions are common. However, RASS's range is generally limited to altitudes of less than 3 km agl. RASS and microwave sounders could be used together at airports to provide the resolution needed at lower altitudes and temperatures above the terminal airspace.

At the present time, there is no explicit capability to range-resolve temperature ahead of an aircraft. Radiometry is the most promising possibility. The NASA Jet Propulsion Lab scans air temperature at high altitudes ahead of an aircraft, with temperature provided at a relatively fixed distance. Though not range-resolved, aircraft motion effectively range-resolves the temperature and thus may provide an interim solution. The efficacy of this system needs additional exploration for icing applications; its performance within clouds is unknown. RASS has been found not to be practical for sensing temperature from aircraft.

There is a possibility of range-resolving air temperature above and below aircraft, at zenith and nadir, with microwave radiometers using the same techniques that are used by ground-based and satellite-based microwave radiometer temperature sounders. The scan times required may cause smearing of temperature due to aircraft motion, approach and descent altitude changes may prevent accurate temperature retrieval because of necessary scan times, and ground radiation may cause problems when sensing to nadir. A zenith/nadir sensing system does not indicate temperature ahead except through extrapolation, although some scanning capability may be possible. However, it would indicate where warm temperatures may exist for escape from icing.

5.2 Introduction

A remote-sensing system designed to detect icing potential ahead of aircraft would consist of three components:

- A suite of detectors to measure conditions that cause icing
- A processing system to integrate information, as it is received from the sensors, to assess the icing hazard
- An information display system to provide pilots with timely, useful maps of the icing hazard.

The sensing system, which acquires the information to provide a measure of icing potential with distance ahead of the aircraft, must accomplish several tasks. First, it must detect, either directly or through the use of surrogates, cloud and precipitation liquid-water content, temperature of the droplets (or the existence of supercooling), and some measure of the breadth of the drop-size spectrum. It must map the magnitude of these conditions ahead of the aircraft for avoidance purposes, and it must locate where icing conditions do not exist ahead of the aircraft for escape purposes if the aircraft is immersed in icing. In addition, the location of each condition must be measured in three-dimensional space often enough to provide a continuously updated image of conditions to the pilot. The system must also scan a sufficiently large volume of atmosphere, to a great enough distance and with sufficient detail, to provide pilots with avoidance and escape options. Since remote sensing is a stand-off technique, sensing systems typically detect and measure phenomena without being immersed them. To effectively assist escape from icing, however, they must also be able to sense that icing conditions do not exist in a volume of air ahead of the aircraft while sensing from within icing conditions.

A variety of technologies are available for remotely sensing atmospheric properties (Westwater and Kropfli 1989). Current technologies are designed to operate from ground positions to zenith or from satellites to nadir. Some sensors can scan the atmosphere at intermediate angles, and some can scan in the horizontal. However, capabilities of some technologies are either enhanced or severely limited by the direction they are sensing, either horizontally or vertically.

Remote sensing of aircraft icing conditions is developing along two parallel paths, depending upon the technology. One requirement is to create an ability to remotely detect icing conditions ahead of aircraft from sensors mounted on the aircraft. However, since more aircraft are exposed to icing in the departure and approach phases of flight, another requirement is to develop ground-based systems that are capable of scanning the airspace around airports. Airport-based sensing systems are likely to be developed before airborne systems because greater technological development has occurred with ground-based systems, and because they present fewer weight, power, and size restrictions.

It is currently unlikely that one technology will be able to sense liquid water, temperature, and elements of the drop-size spectrum, so a remote-sensing system, whether ground-based or airborne, will probably consist of multiple technologies to obtain all the necessary information. Technologies under consideration include radar, lidar, passive microwave radiometers, and radio acoustic sounding systems (RASS).

5.3 Radar

Radar is the most mature technology under consideration. Initially developed in the 1930s by the British, it was first used for detecting weather phenomena immediately after World War II (Battan 1973, Toomay 1982). Weather radar operates in the shorter wavelengths of the microwave spectrum and into the centimeter wavelength spectrum, with longer wavelength (lower frequency) radars used to detect larger drops such as rain and shorter wavelengths used to detect cloud droplets. Radar wavelengths for atmospheric sensing can be specified by band, frequency, or wavelength (Table 1).

As wavelength shortens, the ability to detect smaller drop sizes improves, but range decreases and attenuation by precipitation and other atmospheric constituents such as water vapor increases as well (Houze 1993).

Table 1. Relationships between radar band, frequency, wavelength, and weather parameter sensed.

Band	Nominal frequency (GHz)	Nominal wavelength	Meteorological condition sensed
S	3 GHz	10 cm	Precipitation (NEXRAD)
C	6 GHz	5 cm	Precipitation (ships)
X	10 GHz	3 cm	Precipitation–clouds (aircraft)
Ku	15 GHz	2 cm	Precipitation–clouds
K	30 GHz	1 cm	Precipitation–clouds
K_a	35 GHz	8.7 mm	Cloud droplets
W	94 GHz	3.2 mm	Cloud droplets

The National Weather Service's WSR-88D Doppler radar system is S band; this is the most common wavelength for land-based weather radars because of its ability to detect precipitation-size particles (Crum and Alberty 1993, Houze 1993). C-band radar is a common shipboard radar, and X band is the most common airborne weather radar. Bands with shorter wavelengths than X band suffer from precipitation attenuation, but the shorter wavelengths may also allow detail to be retrieved about precipitation. Most cloud microphysical radar work is currently in the X, K_a, and W bands, but disadvantages of the millimeter wavelengths include increased absorption by water vapor and oxygen and strong extinction by cloud droplets, drizzle, and rain (Klugmann and Judaschke 1996).

Radar detects droplets and ice crystals in the atmosphere because of signal backscatter from droplets. Backscatter occurs as either Rayleigh or Mie scattering. Rayleigh scattering occurs when droplet diameters are significantly smaller than the radar wavelength (Battan 1962). After some absorption by the droplets, the amount of energy backscattered to the radar is proportional to the sixth power of the drop diameter (Battan 1962). Backscatter is also inversely proportional to the fourth power of the wavelength. As drop diameter approaches wavelength in size, backscatter increases, so the strongest backscatter from small droplets occurs from the shortest radar wavelengths (Battan 1962). At wavelengths greater than 3 cm, droplets of 2-mm diameter and smaller are Rayleigh scatterers, and at wavelengths of 10 cm, nearly all drops are Rayleigh scatterers (Battan 1973). Small frozen drops and small ice crystals backscatter about 20% as strongly as liquid drops of the same size (Battan 1962). In all cases, the temperature of droplets must be determined to evaluate fully the amount of water contributing to the backscatter, because attenuation from droplets also has a temperature dependency (Battan 1973, Rinehart 1997).

Attenuation by scattering also increases as wavelength decreases, because more energy is scattered by intervening precipitation and cloud droplets. These are conflicting factors to consider, because as wavelength is decreased to detect cloud drops, attenuation increases, which limits range in high drop concentrations and high liquid-water contents (Battan 1962, Rinehart 1997).

As drop diameter approaches radar wavelength or becomes larger, Rayleigh scattering no longer applies. Instead, Mie scattering occurs, which produces a less predictable backscatter due to complex interactions between energy reflected within the droplet and energy waves traveling along the droplet surface (Toomay 1982). Depending upon the exact ratio of the drop size to the wavelength, these reflections and traveling waves may be additive or subtractive, making the relationship between drop size and backscatter complex and difficult to predict (Battan 1973, Toomay 1982, Rinehart 1997). In addition, backscatter from ice particles vs. liquid drops reverses due to differences in the real part of the complex index of refraction between water and ice, with ice particles providing about 10 times the backscatter energy of liquid drops of a given size (Battan 1962).

Doppler radar measures the motion of drops or ice crystals along the axis of the radar beam (Battan 1973). The fall speed of water drops is related to their size, and the fall speed of ice crystals is related to their size and shape (Rogers and Yau 1989). A vertically oriented radar can distinguish drop sizes, and distinguish drops from ice crystals, by their fall speed. Shorter-wavelength radars have a greater ability to distinguish between fall speeds and thus are better able to resolve drop sizes. Because of the large volume a radar beam senses, and the large number of drops within a given volume of air, a spread of the Doppler spectrum typically occurs, which makes the Doppler signal difficult to interpret. Causes of spread include spread in terminal velocities of the drops or ice crystals within a sensing volume, turbulence, and wind shear across the radar beam (Battan 1973). Although Doppler radar is useful for determining drop-size spectra from ground-based radar, it is likely that Doppler techniques will be difficult from aircraft-mounted radars because most drops will be falling orthogonally to the radar beam, making a Doppler shift less detectable. However, turbulence can cause a Doppler shift because small drops, which are more influenced by turbulence than large drops, can be carried toward or away from the aircraft, allowing their identification.

The polarization of transmitted and received radar energy can be used to determine the mean values and distributions of particle size, shape, and spatial orientation and to determine their phase (Houze 1993, Zrnic 1996). Radar signals may be linearly or circularly polarized. Linearly polarized radars transmit and receive energy in horizontal and vertical planes, principally because falling drops typically shorten in the vertical axis and lengthen in their horizontal axis (Houze 1993). Differential reflectivity and the linear depolarization ratio are computed from horizontal and vertical polarization. Differential reflectivity, the ratio of the horizontal transmitted-to-received energy to the vertical transmitted-to-received energy, typically indicates the oblateness of falling drops—a measure of drop size. Drops smaller than 300 μm are typically spherical, but as size increases, oblateness and differential reflectivity both increase. Ice crystals typically show no differential reflectivity. The linear depolarization ratio, the ratio of horizontally transmitted to vertically received energy, indicates how much of the transmitted signal is depolarized. Wet ice particles produce less depolarization than water drops or dry ice crystals do, so it is a useful method for locating melting layers (Houze 1993, Rinehart 1997).

Circular depolarizing radars transmit a signal that rotates one complete revolution orthogonal to the beam axis per radio frequency cycle (Toomay 1982, Houze 1993). The circular depolarization ratio is the ratio of the parallel (transmitted) component to the orthogonal (received) component and indicates the sphericity of particles. Polarization may be useful for determining some elements of the drop-size spectra, especially from airborne radar that is scanning drops and crystals orthogonal to their falling direction and thus maximizing shape deformation, or long-axis orientation, to the horizontal.

5.3.1 Detection of liquid water

5.3.1.1 S-band radar. The ability to detect raindrop-sized particles may be needed in a remote ice-detection system because freezing rain is a serious aircraft icing threat, although it is typically not considered as dangerous as freezing drizzle. Raindrop sizes begin at about 500 μm diameter and extend to about 5 or 6 mm in thunderstorms (Pruppacher and Klett 1997). It is possible to experience icing in very large drops near the tops of towering cumulus in the tropics or in the midlatitudes in the summer months. However, freezing raindrops will usually be found at the smaller end of the size spectrum, typically no larger than 3 mm, because turbulence is small in most freezing rain (Jeck 1996). According to Battan (1973), S-band 10-cm radar can successfully estimate rainfall rates, and thus liquid-water content, for long distances. The National Weather Service's NEXRAD, for example, is a 10-cm radar with a range of about 460 km for reflectivity measurements. NEXRAD does not provide explicit precipitation liquid-water content at the present time, but it does provide vertically integrated liquid water from rainfall contained in a 4 km by 4 km grid (Crum and Alberty 1993). Thus, precipitation liquid water may be estimated near airports from a ground-based remote detection system. Doviac and Zrnic (1984) indicate that accurate estimates of rainfall rates and rainfall liquid water require a knowledge of the raindrop size distribution, which, if unknown, can cause rainfall rates to differ by a factor of four. In their review of the extensive work that has been done estimating rainfall rates from radar, they indicate that spatially detailed measurements of precipitation liquid water require knowledge of drop sizes unless the drop sizes are reasonably uniform. Curvature of the earth also causes radar to observe different portions of storms with distance and thus different drop-size distributions. Doviak (1983), in a review of rain rate estimation methods using radar, indicated that at that time there was not a satisfactory proven method for estimating rain rate from radar. That situation seems to have changed little; NEXRAD needs to utilize rain gauges for correction (Crum and Alberty 1993, Houze 1993, Rinehart 1997).

5.3.1.2 C-band radar. C-band radars have also been used experimentally to obtain rainfall rates, but again they are too large for aircraft use, though they could be used at airports (Gorgucci and Sarchilli 1996a,b; Tian and Srivastava 1997). Doviac and Zrnic (1984) argue that this ability to measure rainfall rates, along with Doppler detection of wind shear, would be a useful tool for predicting freezing rain at the surface and aloft.

5.3.1.3 X-band radar. X-band radar is small enough to be carried aboard aircraft and often is. It is useful for detecting precipitation, although with less accuracy than longer wavelengths (Rogers and Yau 1989). X band is typically considered a precipitation radar, but it is capable of detecting cloud liquid water. For example, Paluch et al. (1996), comparing the use of X- and K_a-band radars for detecting cloud liquid-water content, found a close, consistent correlation between radar reflectivity and cloud liquid-water content in summer cumulus in Florida. However, they indicated that Bragg scattering—the susceptibility of longer wavelengths to detect "angels" caused by turbulence—was a potentially greater problem with X-band radar (White et al. 1996). They also indicated that there is typically a strong relationship between drop size and reflectivity, which is a source of error in radar liquid-water measurements. In the Florida observations, however, there was a strong reflectivity–liquid-water content relationship because most of the liquid water was concentrated within the large end of the drop-size spectrum. This suggests that broad drop-size spectra will produce a larger rainfall rate estimate error than narrow spectra.

5.3.1.4 Millimeter-band radar. Millimeter-wave radars, principally the K_a and W bands, are the current choices for detecting cloud microphysical properties and precipitation (Mead et al. 1994, Kropfli and Kelly 1996). Since the backscattering cross-section of a drop is inversely proportional to the fourth power of the wavelength, long-wavelength radars, despite their great range and power, are at a disadvantage for detecting cloud droplets. They can compensate with larger antennas and more power, but at high cost (Martner and Kropfli 1993), and, though they may be useful at airports for scanning for icing conditions, they do not fit on aircraft. Kropfli and Kelly (1996) indicate that millimeter-wavelength radars are sensitive to small hydrometeors, have excellent spatial resolution, minimal ground clutter problems (which allows observation of weakly reflecting cloud with high resolution), and are easily portable. However, because of attenuation in moderate to heavy rainfall, they are best used in nonprecipitating clouds. Ice crystals can also cause non-Rayleigh scattering, which causes loss of signal. If combined with a longer-frequency radar, such as X band, differential attenuation can be used to extract cloud liquid-water content (Martner et al. 1991). According to Mead and his colleagues, as of 1994, only five universities and one government laboratory had operating millimeter-wave radars. Applications include studying internal circulations of cumulus clouds, remotely measuring rainfall drop-size distributions, and studying drizzle in stratus clouds (Mead et al. 1994).

Bragg scattering caused by atmospheric refraction, which is a problem for longer-wavelength radars, is negligible for millimeter-wavelength radars (Kropfli and Kelly 1996). However, the short wavelengths often restrict the applicability of Rayleigh scattering. Thus, for K_a-band radar, Mie scattering begins for water drops at about 2.7 mm diameter, and for W-band radar at about 1 mm diameter, which increases the complexity of interpretation. Mie scattering is an even more difficult problem for ice crystals and snowflakes, where Mie theory has not been developed (Kropfli and Kelly 1996). High humidity is also a problem with the shortest wavelengths, such as W band, where its attenuation effects may reduce sensitivity to small drops.

Doppler radar in the millimeter wavelengths excels in measuring drop fall speeds because of its high frequency, which allows high precision. Doppler techniques, as indicated earlier, may be helpful for airport-based sensing systems, but they may not be useful for aircraft-mounted systems unless they are scanned up and down at large angles (Kropfli and Kelly 1996). Polarization measurements may also be used, especially with K_a-band radar, to determine particle shape and orientation (Kropfli and Kelly 1996). For example, the circular depolarization ratio has been used to distinguish plate-like crystals from aggregates in Colorado clouds using a ground-based K_a-band radar, and future capabilities may allow distinguishing between other crystal types.

K_a-band radar can determine cloud base and top, and thus thickness, and cloud structure, which may be useful for avoiding icing (Politovich et al. 1995) when combined with a microwave radiometer capable of measuring vertically integrated liquid water. Vertical cloud liquid-water profiles may be mapped by adjusting drop concentration to force the two signals to fit. Kropfli and Kelly (1996) state that, though W-band radars are superior for airborne use because of their smaller size, the K_a band is less attenuated by water vapor and cloud water, making it more useful. Kropfli and Kelly (1996) summarize millimeter-wave radars by stating that they are severely attenuated by rainfall, but they provide fine-scale measurements of nonprecipitating and drizzle clouds because the amount of energy reflected by cloud droplets and ice crystals sharply increases as wavelength decreases.

There have been many applications of K_a-band radar to measuring cloud microphysics, it appears to be the most useful of the millimeter wavelengths for aircraft icing. K_a band, when compared with the shorter-wavelength W band, can penetrate optically thick clouds with high liquid-water contents, it can detect clouds above light precipitation and multiple cloud layers, and Mie scattering is relatively uncommon (Kropfli et al. 1995). White et al (1996) indicate that K_a-band radar can be used to obtain the reflectivity, Doppler velocity, and Doppler spectral width of drizzle drops. Directly related to reflectivity are drizzle liquid-water content, flux, and number concentration. Doppler velocity and spectral width provide estimates of the magnitudes and shape of the drop-size spectrum. Measurements made during the Atlantic Stratocumulus Transition Experiment (ASTEX) by K_a-band radar provided liquid-water contents from 0.01to 0.14 g m^{-3}, drop diameters from 20 to 320 μm, and drop concentrations from 0.3 to 700 L^{-1}. Kropfli et al. (1995) further demonstrated in ASTEX that K_a-band radar detected ice masses as low as 0.003 g m^{-3} in cirrus clouds at 7-km range. They also demonstrated retrieval of integrated liquid water at zenith, as may be applied at airports, and compared it with radiometer-derived integrated liquid water (Martner and Kropfli 1993). Radar and radiometer-integrated liquid-water estimates compared well except in drizzle.

The University of Massachusetts has developed a dual-wavelength, ground-based cloud-profiling radar system operating at K_a and W bands (Sekelsky and McIntosh 1996). A system with a 1-m-diameter antenna is used to make polarimetric and Doppler measurements of clouds at both wavelengths. The authors state that dual-wavelength millimeter-wave particle sizing (drops and ice crystals) has the potential for more accuracy than single-wavelength Doppler methods. In addition, they indicate that MVD and the shape of drop-size spectra can be determined more accurately with both wavelengths. They speculate that it also may be possible to discriminate glaciated from liquid clouds and to estimate particle sizes in fully glaciated clouds.

W-band radars, operating at about 95 GHz, are becoming increasingly popular for cloud microphysics work (Mead et al. 1994, Kropfli and Kelly 1996). They offer even better size, weight, and power advantages than K_a-band radars, but they also suffer more severely from attenuation in large drops, humidity, and precipitation. They are used to measure cloud structure and excel at observing drizzle, which is a subject of intense study because it is believed to regulate the thermodynamic structure and radiative coupling of the marine boundary layer (Frisch et al. 1995). Lhermitte (1987) developed theory for W-band radar and demonstrated some of its capabilities as a Doppler radar, but he did not measure cloud liquid-water content.

A University of Massachusetts 95-GHz dual-polarized radar for ground-based and airborne use flies on the University of Wyoming King Air research aircraft (Mead et al. 1994). It has a demonstrated range of 0.1 to 2.9 km and has observed 1- to 2-mm graupel with some rimed, branched crystals, crystal aggregates up to 4 mm diameter, and needles up to 1 mm diameter. In a study with this radar, a 30-km segment of shallow stratus producing freezing drizzle was flown. The radar beam, pointing vertically, observed detailed cloud structure at 30-m resolution, and radar backscatter was compared to cloud parameters measured with in-situ instruments. The radar-enhanced interpretation of in-situ measurements was not itself used to measure specific cloud physical parameters. A similar radar, built by the University of Massachusetts and the NASA Jet Propulsion Lab, the Airborne Cloud Radar, flies on a NASA DC-8. More than 50 hours of testing has occurred in cirrus, stratus, and cumulus clouds, and melting layers have been observed (GEWEX 1996).

In other W-band applications, Klugmann and Judaschke (1996) have developed a W-band Doppler radar in Germany to measure vertical velocities within clouds by tracking drop speeds. Clothiaux et al. (1995) also explored the use of W-band radar combined with other remote sensors. They indicate that, when pointed at zenith, W-band radar is valuable for mapping cloud base and top, but base is often indicated as too low because of precipitation. Though methods were not developed to compute cloud liquid-water content from the radar, in-situ measurements of liquid-water content were compared with the radar calibration, and calibrations were consistent with in-situ measurements.

Sassen and Liao (1996) developed theory for measuring the contents of ice and water clouds from W-band radars. They indicate that for most cloud drops, Rayleigh scattering applies in W band, and they provide algorithms for computing cloud liquid and ice content from reflectivities. Fox and Illingworth (1997a,b) computed W-band reflectivity and cloud liquid-water content from more than 4000 km of flight in-situ drop spectra measurements by aircraft. They computed the probability of detecting various values of liquid-water content as a function of radar sensitivity. Computations were complicated by the predominance of drizzle drops in marine stratocumulus. They concluded that a highly sensitive space-based radar could detect 100% of all marine and stratocumulus clouds, but it was not clear if cloud liquid-water content could be directly measured.

5.3.1.5 Liquid-water content retrieval techniques.

5.3.1.5.1 Single-band retrieval techniques. Frisch et al. (1995) develop theory and demonstrate, using the NOAA ETL radar (Martner and Kropfli 1993), the retrieval of drizzle and cloud droplet parameters with a K_a-band radar and a radiometer for measuring integrated liquid water. Doppler techniques were used to measure the drizzle drop-size spectra, and drizzle and cloud liquid-water content were measured from reflectivity. Cloud liquid-water content was computed by using Doppler velocities of drizzle and cloud to parse the two liquid-water contents. Overall, by using K_a-band radar, Doppler features, and a simple drizzle model, the authors were able to extract drop number, size distribution, liquid-water content, and mean liquid-water flux. They indicate that there is a potential for ground-based remote sensors to do long-term monitoring of cloud and drizzle parameters, such as at airports. This radar system in a scanning mode, together with a RASS for measuring temperature profiles, may be an adequate airport-based system.

Liao and Sassen (1994) have also developed a technique, although only as modeled theory, that allows extraction of cloud liquid-water content by linking liquid-water content and reflectivity, assuming a drop concentration of 100 cm^{-3}. The model applies for estimating liquid-water content in nonprecipitating cumulus and stratocumulus clouds. They also developed theory for extracting ice water contents from clouds with K_a-band reflectivity.

5.3.1.5.2 Differential attenuation and dual-band techniques. Combining two radar frequencies and analyzing cloud liquid-water content using differential attenuation has become a preferred method of measuring range-resolved cloud liquid water. According to Martner et al. (1993a), using two radar wavelengths with significantly different liquid-water attenuation coefficients to measure cloud water and ice content was first theorized by Atlas (1954). Martner et al. (1991) and Gosset and Sauvageot (1992) independently developed field tests and additional theory, concluding that the best radar wavelengths were in the X and K_a bands. Sand and Kropfli (1991) patented the concept. According to Martner et al. (1993a), as the radar beams enter a cloud, the K_a band is attenuated more rapidly than the X band. Assuming Rayleigh attenuation, the range derivative of the difference of the reflectivities is proportional to the liquid-water content. Both water and ice contribute to the reflectivity. However, according to Martner et al. (1993b), only the liquid water generates the differential attenuation needed to compute liquid-water content. Thus, the attenuation due to ice is the same for both bands—very small.

According to Gosset and Sauvageot (1992), the dual-wavelength differential attenuation method allows discrimination between the solid and liquid phases in a nonprecipitating cloud and an estimation of water and ice contents. The attenuation of ice is negligible compared with the attenuation of water. Thus, after correction for the temperature of the ice and water particles and the coefficients of attenuation of water and ice, liquid water can be computed from the difference between the reflectivities. They claim that theory indicates that the technique allows the quantity and location of supercooled water to be estimated precisely and easily. An analysis of paired X and K_a bands, and K_a and W bands, concluded that the X- and K_a-band pair was best for both air- and ground-based systems because attenuation of the W band is too high. There are problems with Mie scattering, however, if water drops are large. Gosset and Sauvageot (1992) indicated that, with a knowledge of drop temperature, the technique is useful in mixed clouds and light precipitation. Since liquid-water content at any range gate is proportional to the local range derivative of the reflectivity difference of the two radars, precise absolute calibrations of the radar reflections are not needed because only a change in their relative values with range is important (Martner et al. 1991).

Martner et al. (1991; 1993a,b) have done the most definitive field testing of dual-wavelength X-band and K_a-band radars for measuring supercooled liquid water. During the 1991 NCAR Winter Icing Storms Project (WISP), radars were installed northeast of Boulder, Colorado, and liquid water was measured intermittently from February to April. A steerable microwave radiometer to measure integrated liquid water and occasional research flights through the radar beams were available to verify radar measurements. The radars and radiometer were scanned at an angle of 7.5° above the horizon, and the research aircraft flew up the radar beam. Liquid-water content was analyzed with a least-squares fit between the X- and K_a-band reflectivities for a 4-km window of gates (53 gates of 75 m each). Computed liquid-water content was assigned to the center range gate of the 53 gates and then was shifted out one gate, and the computation was repeated. This was repeated for each gate along the beam from 2.0 to 22.6 km from the radar (Martner et al. 1993a). Cloud temperature, necessary for liquid-water content computations, was either estimated or available from the research aircraft.

Test results during WISP were mixed because of radar design deficiencies due to the low-budget nature of the tests, weather conditions, and inability to obtain complete in-situ measurements of the radar-measured cloud conditions. Seven cases were analyzed from WISP91, five cases in February and March with radiometer and aircraft support and two in April without radiometer or aircraft support. The February and March cases gave highly variable results (Martner et al. 1993b). Measurements were made within upslope clouds in one March case with aircraft-measured liquid-water contents of up to 0.4 g m^{-3}, a cloud droplet MVD of about 15 μm, and no ice crystals. However, the radar measured no liquid-water content. In another case with drizzle, liquid-water contents were occasionally negative, perhaps because drops fell outside of the Rayleigh regime. In the April tests, liquid-water contents of 0.2 to 0.6 g m^{-3} were measured, but no in-situ verification was available.

Martner et al. (1993a,b) have evaluated their measurements extensively. They identify several meteorological conditions that cause problems and radar deficiencies that may be responsible for problems. If non-Rayleigh scattering occurs due to large water drops or ice crystals, there is a reversal of the X– K_a-band reflectivity difference trends, producing negative liquid-water contents. Measurements of liquid-water content may also be particularly poor in regions of large aggregate snowflakes and just below the melting layer where liquid-covered ice crystals occur. In addition, false positive and negative liquid-water contents can occur at locations within clouds where large changes in drop size occur—the boundaries between smaller drops and larger drops. For example, if droplets change from small to large, X-band reflectivity may increase rapidly and K_a band does not—producing a large false positive liquid-water content. The reverse can occur as the beams move from large to small droplets, causing a negative liquid-water content.

Clouds composed of small droplets, typically those of continental origin, are difficult to detect, especially at long range and if liquid-water content is low. Ice crystals within the clouds can help make them visible, but then Rayleigh problems may occur (Martner et al. 1993a,b). Higher-power radars may solve the problem. Overall, Martner et al. (1993a,b) were encouraged by the promise of dual-wavelength differential attenuation to obtain cloud liquid-water content. Most of the problems can be solved, and they indicate that more field trials should be performed with improved hardware and in more favorable weather conditions (Martner et al. 1993a).

Fournier (1993) also proposed a dual X- and K_a-band radar as a terminal aviation weather-sensing system to estimate cloud parameters at distances from 20 to 30 km. He indicates that the radar would be capable of estimating, through differential attenuation, cloud type, visibility, wind fields, median drop diameters, ice vs. liquid-water content, and light and moderate precipitation. Development of this system did not continue beyond the proposal stage, however, because of funding cuts at Transport Canada.

5.3.1.5.3 Multiple-band retrieval of liquid-water content. Considerations for multiple-wavelength radars include the use of more than two wavelengths and relationships beyond differential attenuation. For example, Jameson (1994) develops theory necessary to measure rainfall rate, rain water content, and mass-weighted mean drop diameter from satellite and airborne radars using multiple-wavelength radars. He claims that simple differential attenuation can be used to determine water content. However, three wavelengths—38, 25, and 13 GHz—are necessary to measure rain rate, rain water content, and mass-weighted mean drop diameter. In his summary, Jameson states that two frequencies are needed to measure one parameter, and the measurement of two or three parameters requires at least three, and ideally four, frequencies. Some of these concepts might be applied to measuring icing potential. In a somewhat different approach, Srivastava and Tian (1996) theorize that two radars of the same or nearly the same wavelength, but physically located apart, could be used to improve computations of rainfall through simultaneous use of each radar's attenuation and reflectivity.

A neural-network-based retrieval technique has been developed at Quadrant Engineering and at the University of Massachusetts based upon backscatter information from three radar bands: X, K_a, and W (Mead at al. 1998, Koenig et al. 1999). A neural network was trained to estimate cloud temperature, liquid-water content, and drop mean volume diameters (MeanVD) and mean radar reflectivity diameters (MZD) from the backscatter power measurements from one, two, and three bands. Range resolution was 2 km, and cloud parameters were synthetically created for a wide range of conditions found in precipitating and nonprecipitating stratiform and cumiliform clouds. The neural net was trained with 10,000 cases and tested with 200 cases. Temperature retrievals were not theoretically possible because of radar noise. However, with three radar bands, liquid water was retrieved with less than 0.17 g m^{-3} error, and MeanVD and MZD with less than 16% error. The neural net is currently being evaluated with actual cloud information to determine prediction accuracy.

5.3.2 Detection of mixed-phase conditions and drop-size spectra

In addition to cloud liquid-water content, detection of icing conditions requires information about the location of liquid water vs. ice particles, and about the size distribution of water drops. The latter is particularly important for detecting whether drops are within the drizzle or raindrop size ranges.

The technique most useful for detecting some of these parameters, but especially drop size, depends upon whether the radar is ground-based or airborne. As discussed earlier, Doppler techniques may be used to determine droplet size from the fall speeds, but the radar must attain a high angle scan, near zenith or nadir, to obtain a reliable velocity measurement. Since the range of drop speeds in the drop sizes of interest is small, use of Doppler techniques may be difficult. Cloud drops all fall at less than 27 cm s^{-1}, and drizzle falls from about 27 cm s^{-1} to 2.06 m s^{-1} (Rogers and Yau 1989). Larger drops fall faster.

Polarization relies upon the oblateness of larger drops as they fall and distort in shape due to aerodynamic drag. Since drops smaller than 300 μm in diameter are typically spherical, drop shape cannot be used to determine droplet size in the cloud drop range (Pruppacher and Klett 1997). Depending upon the wavelengths, especially for multiwavelength radars, it may also be possible to use Rayleigh vs. Mie scattering to sort drops by size.

5.3.2.1 Doppler radar techniques. Thomson and List (1996) developed a new method to determine rainfall drop-size spectra with a vertically pointing X-band Doppler radar. Errors in raindrop fall speeds with Doppler radar occur from vertical wind, turbulence, pressure dependence of terminal fall speed, and deviations from Rayleigh scattering. Disdrometer measurements of drop size during radar measurements in the Canadian Atlantic Storms Project indicated that the power spectrum of the raindrop velocities was related to the drop-size spectra. Vertical wind effects were removed, and the drop spectrum was calculated from reflectivity. Good agreement between measurements and radar calculations of drop spectra were found in two test cases.

Gossard (1994) proposed a method for extracting cloud droplet-size spectra information using Doppler radar in the K_a band. Doppler radar typically cannot detect cloud droplet spectra from fall speed because the settling velocity of cloud droplets allows them to be carried by updrafts and downdrafts. Gossard developed a technique, tested on a long-wavelength wind profiler Doppler radar, that allows extraction of the cloud drop-size spectrum by measuring the spectrum shape parameter independently of updrafts and downdrafts. He proposes that the method is effective in detecting drop growth to the drizzle-size range in stratus clouds. The method cannot be used in precipitation because the raindrops overwhelm the cloud signal, and there is too much error in the technique to determine cloud liquid-water content, even with no precipitation. The technique may be applicable at airports with ground-based radars, and it may be useful for airborne radars if high-elevation scanning is performed on clouds above and below the aircraft. Gossard et al. (1997) expand on the technique and indicate that errors in liquid-water content are possible within a factor of two and that relative liquid water and rainfall flux through clouds should be accurate.

Lhermitte (1987) uses W-band Doppler radar to extract information about the rainfall drop-size spectra in clouds. Using Doppler velocity measurements of drop fall speeds, and Rayleigh and Mie scattering, drop sizes were detected in field tests in Florida and Colorado. He proposes that combining several radar wavelengths, such as W, K_a, and X bands, would provide the capability of detecting the full range of raindrop sizes using Doppler techniques. Lhermitte (1988) also presents a method of backing out air vertical velocities from raindrop fall speeds to improve measurement of drop-size spectra. The technique relies upon Mie backscattering oscillations around Mie scattering maxima and minima caused by raindrops of various sizes (Lhermitte 1987). The technique would be useful in providing vertical profiles of drop-size spectra within clouds and could be applied to S-band radars such as NEXRAD.

5.3.2.2 Doppler and polarization radar techniques. Wilson et al. (1997) developed a method of determining parameters of the drop-size distribution of rainfall to estimate rainfall rates. This is accomplished, using S-band radar, by measuring differential Doppler velocity (DDV), the difference between Doppler velocities at vertical and horizontal polarization. DDV is independent of turbulence and most shear. It is used with reflectivity and differential reflectivity to produce a three-parameter gamma fit to the drop-size distribution. The radar beams must have elevation angles of 10° to 40° for accurate measurements. The technique is not affected by drop oscillations and can detect ice crystals and determine the location of melting layers. Because of the radar wavelength, the technique would be usable only with ground-based radars, such as the NEXRAD.

Takahashi et al. (1996) utilized a Doppler and dual-polarized X-band radar system to detect the drop-size distribution of rainfall in isolated cumulus clouds in Japan. Drop-size distribution was computed from terminal fall velocities of the drops and the differential reflectivity and horizontal polarization. Drop sizes larger than 140 μm were detectable. The linear depolarization ratio and the correlation between the vertical and horizontal polarized waves were used to determine mixed-phase layers, such as the bright band. Two parameters of an assumed exponential drop-size distribution were returned by the radar. Measurements made of rainfall in isolated cumulus clouds were plausible, but no in-situ verification measurements were made.

In one of the first modern uses of a K_a-band radar, Kropfli et al. (1982) used a Doppler radar scanning at a high elevation angle, and circular depolarization, to distinguish falling precipitation forms. Fall speed distinguished graupels, aggregates, and dendrites into five categories within a squall line, and the circular depolarization ratio was able to distinguish frozen particles from raindrops. They conclude that the combination of fall speed and the circular depolarization ratio will yield more information than either can individually.

5.3.2.3 Polarization radar techniques. Reinking et al. (1996) proposed and tested a method of differentiating drizzle from rain and ice crystals using elliptical depolarization ratios (EDRs) and linear depolarization ratios (LDRs) with the NOAA ETL scanning K_a-band radar. Drizzle drops are spherical and do not polarize the signals, raindrops are nonspherical and will depolarize the radar signal, and depolarization by ice crystals depends upon their shape and orientation. Scattering calculations, and measurements during WISP in 1993, indicate that EDR provides a good capability to distinguish between ice crystals of various habits, drizzle, and rain. If the requirement is simply to distinguish drizzle from ice, then LDR is better and could be applied to NWS NEXRAD radars for use at airports. Matrosov et al. (1996) and Reinking et al. (1997) have further differentiated ice crystal types using EDR and LDR with drizzle drops as a reference. They are able to discriminate hydrometeor types within cloud systems, which will help determine the presence of cloud ice and drizzle.

Pazmany et al. (1994) described the development of a new W-band dual-polarized Doppler radar at the University of Massachusetts. The radar flies on the University of Wyoming King Air, as described earlier, and operates pointing either horizontally, along the flight path, or vertically. Early tests indicated the ability to detect melting bands and hydrometeor type. Flights with the radar in 1992 and in WISP94 provided airborne in-situ and radar measurements of snowstorms, needle ice crystals, and melting layers. Most observations were made at vertical incidence to clouds above the aircraft. The paired radar and in-situ measurements will be used to develop relationships between the two.

5.3.2.4 Neural net and other radar techniques. Mead and Pazmany (Mead at al. 1998, Koenig et al. 1999) proposed using a three-band radar consisting of X, K_a, and W to detect liquid-water content and elements of the drop-size spectrum, using a neural net for post-processing the radar returns. This technique, described earlier, shows excellent potential for estimating elements of the drop-size spectrum, but it cannot detect mixed-phase conditions.

Using C-band radar, Huggel et al. (1996) improved estimates of rainfall rates by more accurately estimating drop-size distribution. They argue that most liquid precipitation is formed in a bright band where falling ice crystals melt and coalesce into raindrops. By developing a relationship between reflectivity within the “bright band” and measured drop sizes with disdrometers, they were able to predict drop-size distributions below the melting layer in moderate intensity rainfall, from 1 to 10 mm hr^{-1}, in Switzerland.

5.4 Passive microwave radiometers

Microwave radiometers operate by receiving thermal energy emitted and scattered by the earth's atmospheric constituents (Grody 1997). They are passive instruments, receiving natural radiation and actively emitting none of their own. Radiative energy is emitted, scattered, and absorbed by the atmosphere, and radiometers act as thermometers to measure a narrow spectral portion of this energy. Passive microwave radiometers are used to measure many atmospheric and surface characteristics, but their ability to measure atmospheric temperature, cloud liquid-water content, and attributes of cloud and precipitation constituents such as phase is needed for estimating icing hazards. Microwave measurement is based on the brightness temperature of atmospheric constituents. The radiation intensity observed by a radiometer is a function of the temperature, reflectivity, transmissivity, and emissivity of the emitter and attenuation by constituents between the emitter and the radiometer at the specific wavelength of interest.

Each atmospheric constituent—gas, liquid, and solid—has a unique absorption spectrum. The atmosphere in general absorbs in several narrow wavelength bands and allows radiation to be transmitted through several broad windows due to the atmosphere's gaseous composition. The primary absorbers are oxygen and water vapor. Oxygen absorbs and re-emits in the 50–60-GHz region and at 118 GHz and is used for temperature profiling. Water vapor has peak absorption and re-emission at 22, 37, and 183 GHz (Grody 1997). Liquid-water peak absorption and emission occurs near 37 GHz and 89 GHz.

Passive microwave detection of cloud water and precipitation is practical from the ground because the background of space has a low brightness temperature, providing high radiative contrast with clouds. Satellites can detect cloud water and rainfall rates over water bodies because water also provides a low brightness temperature, but land masses are warmer and more radiatively complex, making interpretation difficult. Thus, observation direction is more critical for passive radiometry than for radar, because the latter creates the energy that it observes and so contrast is typically more adequate.

Radiometers are also capable of measuring polarized energy. Polarization describes brightness temperature (radiance) along either a horizontal plane between the emitter and the radiometer—vertical polarization, or along a plane orthogonal to that path—horizontal polarization. Cloud and precipitation drops are usually vertically polarized.

Analysis of microwave attenuation for typical atmospheric paths over a frequency range of 1 to 300 GHz is performed with RADTRAN or similar radiative transfer models* (Falcone et al. 1982). RADTRAN is a design tool to assess potential environmental impacts on microwave sensors. In effect, it allows reasonably complete modeling of the atmospheric radiation environment due to gases and clouds, including polarization, prior to actually building a radiometer.

5.4.1 Detecting liquid-water content

Cloud liquid water and rainfall rates have been observed with radiometers over oceans and over land from the ground, from the air, and from satellites. Observing from the ground up to clouds, or from aloft down to clouds over water, is least difficult because clouds contrast well with the thermally cold background of space or water surfaces. Sensing cloud water from aloft toward the ground is more difficult, as indicated above, because of the radiative diversity of land surfaces. Airport-based radiometers scanning for icing conditions will scan upward toward the cold of space. The situation may be more difficult for aircraft-mounted radiometers because they will scan ahead, above, and below the aircraft flight path and, depending upon the aircraft's flight altitude and attitude, they may be looking at the horizon, toward space, or toward the earth's surface, which could be either land- or water-covered. Thus, sensing cloud water along flight paths may be considerably more complex and difficult than most radiometer sensing to date. In general, cloud liquid water can be sensed with microwave radiometers, but ice is difficult to detect. Thus, cloud-water sensing is not complicated by the presence of ice, but the presence of ice cannot be used to determine whether cloud water is supercooled.

5.4.1.1 Sensing upward from ground. Westwater (1978) reviewed the theory and assessed the accuracy of determining cloud liquid water from upward-looking radiometers. His analysis yielded a two-wavelength system, operating at 30 GHz (1.0-cm- wavelength) and 21 GHz (1.4-cm wavelength) to detect liquid water and water vapor, respectively. Two wavelengths are needed because, if a single-frequency radiometer is used, variations in water vapor cause apparent changes in cloud liquid water (Hill 1991b), though Hill disputes the need for water vapor measurements during the winter (Hill 1991a). Westwater indicates that knowing cloud temperature would improve the accuracy of water vapor and cloud water estimates.

Hogg et al. (1983a,b) describe a dual-frequency

* Statement made by T. Lines, Raytheon Corp., Denver, Colorado, at Inflight Remote Sensing Icing Avoidance Workshop, Meteorological Panel, 2 April 1997.

radiometer at NOAA ETL that measures both integrated water vapor (20.6 GHz) and cloud liquid water (31.6 GHz). Accuracy was determined by comparing with liquid-water estimates derived by microwave transmissions from a COMSTAR satellite through clouds. A scatter plot comparing the two methods showed a nearly 1:1 relationship, with scatter in the 1:1 relationship increasing as liquid water increased. They also demonstrate azimuth scans of the radiometer at an elevation angle of 12.5°, showing liquid-bearing cloud fluctuations depending upon the antenna direction. In heavy rains, such as 80 mm hr^{-1}, the radiometer saturates due to excessive radiation. Signals were not affected by water or snow on the antenna. The authors suggest that an airborne system could scan from the zenith to any angle forward along the line of flight, suggesting that horizontal sensing may be possible.

Gary (1983) describes a microwave system designed to monitor aircraft icing conditions that was demonstrated at Buffalo International Airport. Temperature profiles, water vapor, and cloud liquid water were measured with radiometers. Water vapor and liquid-water measurements were made from radiometers operated at 22.23 and 31.4 GHz, respectively. Water vapor and temperature were verified with radiosondes, but intended overflights to verify liquid water did not occur. However, forecasts of aircraft icing and pilot reports of icing did compare well, suggesting that the liquid-water measurements were reasonable. This study is the first example of a system explicitly designed and tested, using remote-sensing devices, for detecting aircraft icing conditions.

A workshop about remote detection of aircraft icing, sponsored by the University of North Dakota (Smith 1985), concluded that passive microwave radiometers would be useful for determining cloud liquid water. However, since radiometers only provide integrated liquid water, cloud top and base would also have to be measured to provide an estimate of cloud liquid-water content in mass/volume units. They recommend that radiometers be used in scanning mode but indicate that scanning is slow and would take about 5 min per 360° scan at one elevation angle. A solution to this may be to use multiple radiometers, each scanning assigned sectors and elevation angles.

Fotino et al. (1986) related radiometer-derived zenith measurements of temperature and liquid water near Denver to pilot reports of icing. Frequencies of 20.6 GHz and 31.65 GHz were use to measure water vapor and liquid water, respectively. Measurements were integrated over 2-min periods. Comparisons with pilot reports were difficult because they are often inaccurate in time and location, and pilots avoid icing upon hearing reports of the conditions. They found overall strong correlations between the radiometer measurements and icing pilot reports. Westwater and Kropfli (1989) cite Fotino's work as one among several demonstrating the utility of scanning microwave radiometers at airports for detecting aircraft icing conditions. They stress the importance of the 21-GHz and 31-GHz frequencies for measuring integrated liquid water. They demonstrate how the radiometers can be used to continuously map integrated liquid water, and they indicate that 90.0 GHz is also a frequency that can be used to detect liquid water. It is six times more sensitive than 31 GHz, and can measure integrated liquid per unit area ranging in magnitude from 0.03 to 5.0 mm, which translates to 0.06 to 10.0 g m^{-3} of cloud water. This higher sensitivity is confirmed by Grody (1997), who indicates, however, that scattering from precipitation droplets is a serious problem at 85–90 GHz.

Hill (1991a, 1992) made some of the first measurements comparing radiometer-measured supercooled liquid water with in-situ aircraft measurements. The Utah State University radiometer, a copy of the NOAA ETL scanning radiometer discussed above, operates at 20.6 and 31.65 GHz. Field tests were done at Sodus Point, N.Y. A research aircraft carrying a Rosemount ice detector to measure supercooled liquid water was flown in ascending and descending spirals centered over the radiometer. Measured liquid-water contents were low, near the limits of the radiometer resolutions, so completely valid comparisons could not be made. Seven validation tests were made, with two producing spuriously high readings by the radiometer, potentially attributable to cloud-entrained snowfall that did not adhere to the ice detector and a melt layer along an inversion.

Hill (1991b) also compared the ability of a dual-frequency radiometer, the Utah State instrument cited above, and a single-frequency radiometer operating at 31.65 GHz to measure cloud water. A dual-frequency unit corrects cloud water content by accounting for changes in water vapor. However, according to Hill, these changes are very small during the winter and introduce little error if ignored. A comparison between the two radiometers during winter tests indicated a nearly 1:1 relationship, suggesting that the winter water vapor correction is not needed. This would simplify cloud-water measurements from aircraft, reducing hardware and computational requirements.

Stankov et al. (1992) describe the use of four microwave radiometers to measure supercooled liquid water in the Denver and Boulder area during WISP91. Though the radiometer estimates of liquid water were not explicitly compared with aircraft measurements, they conclude that the radiometer's ability to measure liquid water was excellent. The only reported problem with the radiometers involved keeping snow from adhering to the sensor windows.

Martner et al. (1993a), as part of the Lake Ontario Winter Storms project, installed Doppler radar, wind profilers, and microwave radiometers to measure integrated liquid water on the eastern shore of Lake Ontario. A freezing rainstorm on 15 February 1990 was continuously monitored by the microwave radiometers at 20.6, 31.65, and 90.0 GHz. Vertically pointing scans and scans at a 7.5° elevation angle were made. The radiometer could not observe snow and ice, but it immediately signaled the onset of melting aloft at the beginning of liquid precipitation. Some overestimates of liquid water may have occurred because water-coated snowflakes appeared to the radiometer to be completely liquid water as they melted. In addition, high emission during rainfall occasionally saturated the radiometer signal. The radiometers were valuable for their ability to observe the immediate onset of freezing precipitation aloft.

Huggins (1995) describes the use of a dual-wavelength radiometer system (20.6 and 31.65 GHz), similar to the ETL system but mounted on a truck for mobile use. The system was used to monitor the spatial distribution of liquid water over the Wasatch Plateau of Utah for cloud seeding. A unique spinning mirror system was used to keep snow and rain off the radiometer mirror.

Most microwave radiometers measure integrated liquid water; they provide no indication of the distribution of liquid water vertically through a cloud. The distribution of liquid water within a cloud layer, and among layers if there is more than one layer, is needed for accurate aircraft icing estimates. Stankov et al. (1995) melded climatological and iterative techniques that had been used unsuccessfully in the past into a new technique using K_a-band radar, wind profilers, and ceilometers. Their goals were to determine cloud base height, cloud top, and cloud layers. Then, using temperature profiles and three different assumptions about the distribution of water within clouds, they parsed integrated water measured by the radiometers through the clouds. These experimental techniques were compared with aircraft measurements as part of WISP. Results were mixed: some profiles compared well with aircraft measurements, and others compared poorly within the same storm. Stankov and his colleagues indicated that more comparisons are needed. This work demonstrates a fundamental need for methods of distributing liquid water through clouds after total integrated values are measured. This is important for determining the concentrations of supercooled liquid water in each cloud profile.

Sauvageot (1996) has developed a method for constructing vertical profiles of liquid and ice water in mixed-phase clouds using a microwave radiometer to determine total integrated liquid water, a Doppler radar to determine updraft velocities, and theory to explain the production of ice crystals and water in rising air. The process operates only in clouds with updrafts. Air temperature and Doppler radar measurements of updrafts are used to describe the rate of production of water vapor in excess of saturation with respect to ice. The radar reflectivity is inverted to determine the profile of ice-particle size distribution. From the ice-particle size distribution, the rate that water vapor can be consumed by pure deposition is determined. The difference between the rate of water vapor production and deposition on ice crystals is the production of supercooled liquid water at each level within the cloud. This technique was simulated, but no field studies have been conducted to demonstrate its viability.

Solheim and Godwin (1998) describe the development of a passive microwave radiometer that profiles atmospheric temperature, water vapor, and liquid cloud water. Operating at two frequencies, the radiometer profiles water vapor by frequency scanning near 22 GHz and temperature and liquid-water profiles by scanning near 60 GHz. Initial use demonstrates radiometer profiles using a variety of retrieval algorithms compared with radiosonde profiles. The instrument, although it needs additional testing, holds promise for providing temperature and liquid-water profiles at airports to assess aircraft icing conditions.

The effects of rainfall on integrated cloud liquid-water measurements also demand attention because rainfall causes cloud liquid water to be underestimated in the 20–90-GHz range. Sheppard (1996) examined the effect of rainfall rate on vertically pointing microwave radiometer measurements of integrated liquid water. Using a radiative transfer model, the amount of error in estimated cloud liquid water increased with rainfall rate. The theory was tested against measurements made in CASP. Sheppard indicates that a future study should investigate the effects of solid precipitation.

5.4.1.2 Sensing from satellites or aircraft over water or land. Passive microwave sensing of cloud liquid water from a satellite or aircraft over land or water is more difficult than viewing toward zenith from below clouds. When observing toward the earth's surface, as explained earlier, the brightness temperature of water and land surfaces must be considered. When viewing toward space, background temperature is near absolute zero (~3°K) and clouds emit strongly in contrast. When viewing toward water bodies from above clouds, the water bodies appear cold, with brightness temperatures of about 140°K at 37 GHz (this can vary by 15°K or more), because the emissivity of water bodies is about 0.5 (Jones and Vonder Haar 1990, Greenwald et al. 1993). Land surfaces typically have larger brightness temperatures than water because land surfaces are often warmer, their emissivity is close to 1, surface roughness and vegetation contribute to variability, and, most importantly, soil moisture varies widely and radiates strongly (Jones and Vonder Haar 1990). This larger and more variable emmitance over land requires different retrieval techniques than over water. The above explanation also suggests why, in principle, sensing cloud liquid water from the ground should be, and is, more accurate, with values typically being correct within 15%, as demonstrated by Hill (1992).

5.4.1.2.1 Liquid-water retrieval over water. Retrieval over water is relatively direct, and techniques for retrieving cloud liquid water over the oceans have been in use for about 20 years with some of the original techniques developed by Grody (1997). Schemes to retrieve liquid water from microwave emissions are statistical, semi-statistical, and semiphysical (Greenwald et al. 1993). Greenwald and his colleagues developed a simple physical technique that is accurate and has been rigorously verified, unlike many other methods. Verification was against ground-based microwave radiometers looking skyward detecting cloud liquid water at four oceanic locations. Relative errors in the algorithm range from 20 to 40%, and occasionally to 50%, with the largest errors in areas with low liquid-water content and thin clouds. The algorithm is also only valid for nonprecipitating clouds, because liquid precipitation radiates strongly. Frozen precipitation does not cause problems because ice is typically not visible at microwave wavelengths.

Lee et al. (1994) applied the Defense Meteorological Satellite special sensor microwave/imager (DMSP SSM/I) in an attempt to predict aircraft icing over ocean areas. They utilized a statistical retrieval algorithm to convert transmittance to cloud water using the 37-GHz and 85-GHz bands. Though heavy precipitation contaminates 37-GHz retrievals, according to Lee and Clarke supercooled water and significant precipitation are mutually exclusive and thus reduce the magnitude of the problem. Most analyses, however, were performed with the 85-GHz band because it has higher resolution. Aircraft icing was expected when liquid water was greater than 0.2 kg m^{-2} and temperatures were between 0°C and –20°C.

5.4.1.2.2 Liquid water retrieval over land. Microwave retrievals over land are possible if emittance from the land surface can be accounted for. In addition, the retrieval wavelength is changed over land to 85.5 GHz, which is more sensitive to cloud liquid water than are other microwave channels, and surface effects become less important as cloud liquid water increases and atmospheric attenuation obscures the ground at this frequency. Jones and Vonder Haar (1990) and Greenwald et al. (1997a) developed methods of subtracting surface effects prior to sensing clouds. A two-stage algorithm, developed by Jones and Vonder Haar (1990), estimates ground transmittance on clear days, and then, after clouds move over, removes the effects of ground transmittance. Greenwald et al. (1997b) further advanced the technique by using the polarization differences of the brightness temperature effective over some land surfaces. The advantage of polarization is that it improves the ability to estimate the liquid-water content of low-lying clouds. Comparisons with ground-based radiometer measurements in Colorado were generally good. This method would be difficult to apply to in-flight detection of cloud liquid water because *a priori* ground radiance information would be difficult to obtain.

5.4.1.2.3 Liquid-water retrieval from the horizontal. Savage et al. (1999) have developed a technique for locating and estimating cloud liquid-water content using two frequencies, 37 and 89 GHz, and three viewing angles. A radiometer placed on the nose of an aircraft would scan horizontally ahead of the aircraft and 2° above and below the flight path. In a clear-sky condition, the +2° beam sees colder temperatures, observing toward cold space, than does the –2° beam observing toward the warmer surface of the earth. As the aircraft approaches a cloud, the temperature of both beams converges toward that of the horizontal beam. During this process, the horizontal beam provides an estimate of the cloud temperature. An estimate of liquid-water content magnitude is obtained by comparing the brightness temperatures of the 37- and 89-GHz beams in the +2° orientation. Since the 37-GHz beam penetrates farther than the 89-GHz beam, it will be colder than the 89-GHz beam if there is little liquid water, because it can detect the cold of space through the water. As liquid-water content increases, the +2° 89- and 37-GHz brightness temperatures converge as cold space is obscured. Savage et al. (1999) also believe that the presence of drizzle-size drops can be detected by sensing polarized radiation scattered from the earth's surface by large drops. The Savage techniques are being evaluated using information gathered during the MWISP field project.

These examples of microwave radiometer capabilities over land and water surfaces represent only a small portion of all work accomplished, but cloud water retrieval over land is new and is not yet available operationally.* Precipitation retrieval from satellites over water and land has been developed even more than cloud water retrieval; it is presented in papers by Spencer et al. (1989), Petty and Katsaros (1992), Vivekanandan et al. (1993), and Ferraro and Marks (1996).

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* Personal communication, J. Vivekanandan, National Center for Atmospheric Research, Boulder, Colorado, 1997.

5.4.2 Drop-size spectra and cloud phase

The only research found that described detection of cloud drop size with microwave radiometers was that of Savage et al. (1999), described above. Generally, cloud ice particles cannot be detected by microwave radiometers because ice is transparent to microwaves. However, Wu (1987) applied four channels of NASA's Advanced Microwave Moisture Sounder, flown on high-altitude aircraft, to the problem of detecting the ice-water content of clouds in the microwave frequencies of 92-, 183- (±2), 183- (±5), and 183- (±9) GHz bands. A microwave radiativex transfer routine was developed that allows detection of the ice-water concentration through mixed-phase clouds by observing the changes in brightness temperature of each frequency. Some success was claimed by comparing computed ice-water contents with observations made in the near-infrared during the Cooperative Convection Precipitation Experiment. The study also showed that cloud brightness temperature at each frequency depended not only on total ice-water content of a cloud, but also on its distribution within the cloud. Further developments of Wu's technique have not been published in the last decade, so it is not clear whether the technique is fully viable.

5.5 Lidar

Lidar, or light detection and ranging, is the optical equivalent of radar, operating in the visible and infrared wavelengths. Unlike radar, however, wavelengths used for lidar suffer rapid extinction in optically thick clouds, so their use for sensing cloud properties is limited. Cloud scattering rapidly attenuates the signal, preventing most lidars from penetrating dense clouds for more than a few hundred meters. However, multiple scattering of lidar returns from clouds can be used to advantage for interpreting elements of cloud composition.

Overall, lidar may be able to contribute to aircraft icing avoidance by remotely sensing cloud conditions, but only in very specific and limited ways because of the extinction problem. An ideal supercooled liquid-water sensor will range-resolve liquid water and drop size many kilometers ahead of an aircraft, even if the aircraft is flying within clouds. A lidar operates effectively only when the aircraft is flying within a nearly cloud-free atmosphere. Lidar can sense through cloud-free atmosphere to the nearest clouds and determine the properties of the first few hundred meters of those clouds, but it cannot penetrate them to determine what lies beyond. Therefore, lidar can only help aircraft avoid icing conditions by determining whether there are clouds in the immediate flight path and if they are conducive to airframe icing. If the clouds are not conducive to icing, they may be penetrated, but the hazard is that clouds beyond cannot be sensed if there is no cloud-free space ahead of them, so aircraft flying IFR cannot use lidar to maximum advantage. Lidar could indicate to night VFR aircraft whether cloud lies ahead, and it could indicate whether liquid precipitation that could be freezing also lies ahead below clouds, giving the aircraft advance warning. Thus, lidar appears to have the greatest utility to night VFR pilots who have multiple reasons to avoid clouds and may need to avoid precipitation. Lidar is of greatest potential utility for avoiding icing and of least potential utility for escaping icing.

Lidar can operate over a range of wavelengths, it can be polarized, and it can be used in single-scattering and multiple-scattering modes where multiple-field-of-view lidars can utilize the information. Its most typical cloud uses are for determining liquid-water content, phase, drop number, mean drop size, and optical thickness. Lidar is also widely used to determine ceiling height, though there is often difficulty with optically thin clouds, virga, and precipitation.

Using an infrared-wavelength CO_2 lidar operating at 10.6 μm, Eberhard (1993) developed theory and demonstrated retrieval of the mean radius of cloud drop-size distributions. The lidar determines the extinction-to-backscatter ratio, which is then fitted to a variety of expected drop-size distributions until a fit is obtained. The method is valid for distributions with drop sizes falling between 1 and 17 μm. Data from fair-weather cumulus clouds at Cape Kennedy provided reasonable results, although no in-situ measurements were available for validation. Eberhard indicated that an 11-μm wavelength may provide better results.

Bissonnette and Hutt (Hutt et al. 1994; Bissonnette and Hutt 1995a,b) at the Defence Research Establishment at Valcartier, Quebec, Canada, have used the backscattered power from a 1.06-μm multiple-field-of-view (MFOV) polarized lidar to characterize cloud, fog, and aerosols. The system measures the backscatter from a central beam with 1.5-m-long pulses and multiscattered return signal intensity at three or more coaxial fields of view with a maximum of ten possible fields of view. The amount of scatter returned is proportional to the number density of drops in the cloud. Fitted to a multiple scattering lidar equation, the measurements provide a scattering coefficient and a droplet effective radius. From this, and an assumed gamma drop-size distribution, liquid-water content and extinction coefficients are computed. Range-resolved droplet size distribution (1 to ~100 μm), liquid-water content to 1.0 g m^{-3}, and extinction coefficient measurements have been made at ranges to 1000 m and verified in situ (Bissonnette et al. 1998). The linear polarization ratio, between parallel and perpendicular polarization, is about 35 to 40%

when clouds are composed primarily of ice crystals. The 1.06-µm-wavelength is not eye-safe, but an eye-safe 1.54- or 2.0-µm lidar could be built with 1.5- to 3.0-m resolution and a 100-Hz pulse repetition rate. Temperature at the cloud could also be determined by ranging with the lidar and sensing temperature with an IR radiometer. Evidence of supercooling could also be assessed using polarization techniques to determine if the cloud is mixed phase.

Benayahu et al. (1995) developed a method for retrieving drop number and drop-size distribution from clouds, and potentially liquid-water content, assuming multiple scattering occurs at all times. A total scatter signal and multiple scattering signal, simultaneously received from two separated receivers, contained information about the shape of the drop-size distribution and the mean droplet radius. A field test was conducted on a marine stratus cloud off the coast of Israel with concurrent lidar and in-situ aircraft measurements, with good agreement between the measurements.

Eberhard (1995), working with a CO_2 laser, argues that depolarization in longer wavelengths cannot be used to discriminate ice from water in clouds. However, the ratio of backscatter between two different wavelengths can indicate the presence of ice. Seven wavelengths between 10.4 and 11.5 µm were selected and paired to test the theory, and the backscatter ratio between water and ice was shown to range from 2 to 5 depending upon the frequency pairs chosen. The method demonstrated the feasibility of detecting ice vs. water without polarization and estimated an approximate proportion of ice vs. water. No field tests were conducted to verify the method, though they were planned. The technique is simple and eye safe.

When a laser beam is incident upon water droplets, most of the energy is scattered away from the drop without change but scatters a small portion of the light at different wavelengths. The scattering of light at different wavelengths is Raman scattering, actually an exchange of energy between a photon and a molecule with a resulting change in the energy—and thus wavelength—of the photon (Carey 1987). Raman scattering has become a useful technique for atmospheric sensing of nitrogen, oxygen, and water vapor and for temperature profiling. Melfi et al. (1997) report on a potential use of Raman scattering for measuring the liquid-water content of clouds. During water-vapor measurements with a XeF laser centered at 0.35 µm, they detected two thin cloud layers as they passed over the lidar. Melfi et al. (1997) indicate that Raman lidar techniques hold promise as a new method for remotely measuring cloud liquid-water content and drop-size distribution. However, because Raman systems are large and expensive and can only be used at night, their application to aircraft icing is unlikely.

In general, lidars have limited use for remotely detecting aircraft icing conditions because of their limited ability to penetrate clouds. Many ground-based and airborne lidars are currently used for boundary-layer research and wind-shear monitoring (Targ et al. 1991, Hannon and Henderson 1995). Canadian organizations interested in aircraft icing have proposed a remote-sensing system for detecting icing conditions that may use lidar as a principal component (EWA 1996). Therefore, though not as promising for penetration of clouds, lidar does have demonstrated capability and may be a candidate technology for limited and specialized applications.

5.6 Temperature measurement

Drop temperature, or a surrogate for drop temperature, is necessary to determine if liquid cloud water is supercooled. In most cases, drop temperatures will be nearly the same as the air temperature, neglecting radiative exchanges, but droplets can be considerably different from air temperature in several situations. Snow falling into warm air, such as in overrunning, will melt. The temperature of snow and ice crystals will rise to 0°C until melting is complete, and then they will continue to warm. These drops may then fall into colder air below and remain warmer than the air until conduction, convection, radiative exchange, and evaporation cools them to the dew-point temperature.

There likely will be little choice whether to measure drop temperature or air temperature, because some sensing technologies may preferentially sense water drops or ice crystals and others may preferentially sense air temperature. A surrogate for air-temperature measurements is the detection of ice crystals. If a cloud is mixed phase, then it is likely that any liquid water is supercooled. Ice crystals may be detected by radar and lidar. Ice detection methods were discussed above, so they will not be dealt with here.

There are at least four types of sensors for measuring temperature profiles:

- Microwave radiometers
- Infrared radiometers
- Radio acoustic sounding (RASS)
- Raman lidar.

Radiative techniques are infrared and millimeter wave, acoustic systems are based on tracking the speed of sound by radar, and lidars detect Raman scattering. The purpose of this review is to indicate how temperature is measured remotely in the atmosphere and to indi-

* Personal communication, L. Bissonnette, Defence Research Establishment, Valcartier, Quebec, Canada, 1997.

cate which methods may be most viable for remote sensing of aircraft icing conditions.

5.6.1 Infrared radiometers

Infrared radiometers are not sounders; temperatures obtained are an integration of the cloud boundary layer, depending upon cloud optical depth, and the depth from which contributing radiating energy originates. Examples of infrared thermal imagers are 10.8- and 11.8-μm sensors of the NOAA Advanced Very High Resolution Radiometer used to determine cloud-top temperatures (Giraud et al. 1997, Lee 1997). Bissonnette* suggests that cloud temperature could be determined in a standoff situation using an infrared radiometer and range determined by lidar. This method would not be viable within cloud, however, because the temperature provided would represent an integration of the cloud mass only a few hundred meters ahead of the aircraft, depending upon cloud optical depth.

5.6.2 Microwave radiometers

Microwave temperature sounders detect temperature changes with altitude by either sensing from the ground to zenith or from satellites to nadir. Oxygen absorbs and thus re-emits in the 60-GHz region (±10 GHz) and at 118.75 GHz. About 45 absorption lines centered on 60 GHz are used to determine temperature with height in the atmosphere by pressure broadening (Grody 1997). The absorption lines found in the ±10 GHz region around 60 GHz result from decreasing atmospheric pressure with altitude (Elachi 1987). Oxygen molecular collisions are frequent enough that at given pressures they reach a local thermodynamic equilibrium. This results in a shift in the wavelength of emission around 60 GHz as pressure changes with altitude, with lines of maximum emission shifting closer to 60 GHz with altitude. That is, the spectrum of wavelength from which oxygen emits radiation near 60 Hz narrows as pressure decreases with altitude. As a result, temperature can be retrieved with altitude by using the expected wavelengths of emission of oxygen at given altitudes. Measurements are typically made on either side of 60 GHz.

Microwave sounders routinely retrieve temperatures with height (Westwater and Grody 1980, Westwater et al. 1983, Askne 1987, Gary 1989, Solheim and Godwin 1998). The primary problem with satellite and ground-based radiometers is their inability to detect rapid changes in temperature with altitude, such as inversions, in the lower few kilometers of the atmosphere (Westwater 1997). However, overall accuracy of ground-based radiometers is typically better than 1.2°C root mean square error (rms) in the lowest 3000 m of the atmosphere. Radiometers still do not have sufficient accuracy or resolution with height to replace radiosondes. When comparing the accuracy of radiosondes, RASS, and radiometers for temperature profiling, Schroeder (1990) determined that the three devices compared well in the summer when temperature changes with height were not rapid, but during the winter the RASS clearly provided better resolution.

Decker et al. (1978) constructed a radiometer system operating around 60 GHz that scanned to an elevation angle of 45° from zenith. They indicated that temperature retrievals are possible from elevation angles other than zenith, though they chose not to report on them. The Solheim and Godwin (1998) microwave radiometer discussed earlier profiles temperature, water vapor, and liquid water at zenith and at low elevation angles.

Gary et al. (1992) report on an automatic temperature profiler operated on the NASA ER-2 high-altitude aircraft. The radiometer, operating at 60 GHz, scans in 10 angular steps from 50° below the flight path to 60° above the flight path ahead of the aircraft. Brightness temperatures from 15 distinct altitudes span from 2 km below the aircraft to 3 km above it. Temperature retrieval accuracy is a function of distance from the aircraft, with greater distance causing greater uncertainty. Measurements are not range gated. However, as the aircraft flies, if scanning is rapid enough, temperatures measured several kilometers ahead of the aircraft can be assembled to create a composite temperature map. Such maps have been assembled by the authors to create altitude temperature profiles and horizontal profiles of temperature. This profiling technique may be promising for detecting temperature ahead of aircraft in an icing environment. It deserves further exploration, but the instrument's capabilities within clouds are unknown.

5.6.3 Radio acoustic sounding systems (RASS)

RASS is used operationally by NOAA; it operates by directing acoustic waves, typically at 900 Hz, vertically into the atmosphere (Schroeder 1990, Matuura et al. 1986, May et al. 1989). Compression and rarefaction by the sound wave alters the air's dielectric constant, allowing radar reflection. A strong reflection is obtained when the acoustic signal is matched to half of the radar wavelength, creating Bragg scattering (May et al. 1988). NOAA uses 404-MHz Doppler radar to track the acoustic wave, the same radars that are used for wind profiling (Westwater 1997).

RASS is generally immune to cloud effects, but there are other sources of error. Humidity changes the speed of sound and, if not considered, can cause errors of up to 2.2°C, and vertical wind velocities of 3 m s^{-1} can produce a nearly 7°C temperature error (North et al.

* Personal communication, L. Bissonnette, Defence Research Establishment, Valcartier, Quebec, Canada, 1997.

1973). The NOAA wind profilers are capable of measuring temperature accurately in horizontal and vertical wind by averaging over a long time period, about 6 min, and by using multiple acoustic sources. Vertical wind errors have been experimentally reduced to as low as 0.1°C using 6-min averaging times (Angevine and Ecklund 1994). Overall RASS accuracies are comparable to radiosondes, with overall error consistently about 1°C rms, with altitudes of 3.5 km agl reached 50% of the time (Westwater 1997). Experimentally, RASS measurements have been made to 15 km altitude and more (Matuura et al. 1986).

RASS is certainly a viable technique for sensing temperature from the ground during icing conditions around airports. Its only limitation at airports may be an occasional inability to reach needed altitudes. Use of RASS in airborne applications, especially sensing ahead of the aircraft, has been assessed to be impractical because of problems with aircraft pitch and yaw and cross winds causing loss of signal (Mead et al. 1998).

5.6.4 Raman lidar

Raman lidar techniques, discussed above, are also used to measure atmospheric temperature profiles (Gill et al. 1979, Evans et al. 1997). Raman lidar uses a variety of wavelengths, with examples at 0.55 and 0.35 µm (Evans et al. 1997, Vaughan et al. 1993). Raman lidar is typically operated only at night because the signal is overwhelmed by solar radiation. Long integration times of 10 min are often necessary to obtain accurate temperatures (Evans et al. 1997). In addition, it suffers from the typical extinction problems suffered by all lidars in clouds. As a result, Raman lidar would not be practical for ground or aircraft-mounted remote sensing in icing conditions.

There are few known remote temperature-measuring methods suitable for operation from airborne platforms in icing conditions. The best possibilities lie with scanning microwave radiometers, but they scan slowly and may be difficult to use from a moving platform. Lidar methods are not practical, and infrared radiometers operated in the 3.8- to 16.8-µm region have a short range in clouds because of reduced optical depth. For ground-based systems, RASS and radiometers are proven and thus offer the best prospects of success.

6.0 RECOMMENDATIONS

Development of a remote-sensing system to detect icing potential requires developers and users to be adept, to adapt, and to adopt (Deffeyes 1996). Adept means that developers have a sufficient understanding of the operational, meteorological, and sensor technology issues to develop a coherent product that addresses user needs. Though research and development may be accomplished through partnering, purchasing, and in-house work, managers must acquire expertise to understand and properly direct activities. They must have the understanding, focus, and comprehensive vision to complete the project.

Adapt means to take technology and skills and adapt it to needs (Deffeyes 1996). A full understanding of the needs, operations, environment, and technologies available allows developers to adapt existing or developing technologies and techniques to the requirements of the product. This means, for example, adapting microwave radiometers or differential attenuation radar to operate on aircraft with other sensors as a system to satisfy the icing information needs of operators and pilots.

Adopt means to acquire new ways of thinking and of doing business (Deffeyes 1996). This will be necessary for system developers, as well as for regulatory bodies, manufacturers, operators, and pilots. Adopting new techniques may improve efficiency and safety, but it requires willingness to change. For example, FAR 25, Appendix C, has been the standard for aircraft design criteria in icing conditions. As new information is acquired characterizing the icing environment, users of Appendix C may be required to change the range of conditions for certifying aircraft for flight in icing conditions.

A logical initial location to provide icing protection using remote-sensing technology is at airports. The need for ice protection is greatest in the approach and departure phases of flight because aircraft are operating at lower altitudes, lingering in conditions for longer periods at slower speeds, and operating closer to maneuvering limits. Protecting airports would also provide the greatest benefit for the least cost.

The ability to sense cloud microphysical properties remotely from the earth's surface is mature in some technology areas. For example, RASS is a mature technology for measuring temperature profiles in the lower atmosphere. Passive microwave radiometers are mature, but have less resolution than RASS for measuring temperature profiles from the surface to midtroposphere altitudes. Integrated liquid-water measurements may be made from the earth's surface using microwave radiometers, and the technology is mature. Liquid water may be distributed among clouds with lidar ceilometers used to determine cloud base and K_a- or W-band radar to determine cloud base and top locations, the locations of multiple cloud layers, and, if needed, cloud phase, or the new radiometer that profiles temperature, water vapor, and cloud liquid water may be a viable option. A system composed of this hardware, driven by expert system logic, and perhaps supplemented with satellite information, would make a usable prototype airport-based remote-sensing system for mapping icing potential. A prototype ground-based demonstration system would allow operational and technological problems to be identified and resolved before airborne systems reach a similar stage of development. Airborne systems are much further from prototype system demonstration because little promising technology is near maturity.

The following recommendations for research are presented for operations, meteorological sensing needs, and technology.

6.1 Operational needs research

- Assess human factors issues of remote-sensing systems, assess cockpit and aircraft integration issues, and develop avoid-and-exit protocol and training.
- Assess integration into the weather system infrastructure for other aircraft, air traffic controllers, and meteorologists.
- Identify aircraft flight envelopes in icing conditions and characterize the icing hazard.

6.2 Meteorological needs research

- Characterize absolute magnitudes of the cloud microphysical conditions that produce icing.
- Assess the spatial and temporal variability of icing weather conditions at multiple scales.
- Develop an icing metric algorithm to convert liquid-water content, temperature, and elements of the drop spectra into a measure of icing potential.

6.3 Technology needs research

- Assess the feasibility of remote-sensing technologies to provide liquid-water content, drop size, and temperature information.
- Develop methods of assessing feasibility studies through measurements with hardware.
- Develop prototype technologies for field testing.

7.0 GOVERNMENT ROLES, MISSIONS AND COLLABORATIVE ACTIVITIES

7.1 NASA

NASA is the U.S. government agency primarily responsible for aviation research. NACA, NASA's predecessor, conducted pioneering icing research in the 1940s that continues today, principally at the Glenn Research Center at Lewis Field in Cleveland, Ohio. In February 1997, President Clinton released the recommendations of the White House Commission on Aviation Safety and Security for improving aviation safety. In response, NASA implemented the Aviation Safety Program, a $500-million program to improve aviation safety in six areas, including weather. The weather requirements include the need to detect icing conditions remotely.

7.2 FAA

The FAA is the U.S. government agency responsible for aviation operations and safety. It implemented the FAA Inflight Aircraft Icing Plan in April 1997 after three meetings examining causes, and solutions to the causes, of the October 1994 ATR-72 crash.

In-flight icing is recognized as a significant hazard to both civilian and military aviation. In May 1996, the FAA held an International Conference on Aircraft Icing in Springfield, Virginia, attended by over 400 civilian and military participants from 20 countries. As a result of the conference, the development of in-flight ice detection emerged as a goal to "accelerate development of airborne technologies that remotely assess icing conditions by working with groups that already are supporting research in this area." In response, the NASA Glenn Research Center, the FAA Technical Center, and CRREL organized a cooperative research program to accelerate development of systems for remotely detecting icing conditions in the flight path.

7.3 NCAR

The National Center for Atmospheric Research, funded by UCAR, which is in turn funded by the National Science Foundation, is the nation's preeminent meteorological research organization. With NASA, the FAA, and Canada's Atmospheric Environment Service, NCAR has led the nation in aircraft icing weather research for several decades and will continue in that role. NCAR excels in developing forecast ability, instrumentation, and atmospheric characterization. In addition, NCAR operates airborne research platforms well-suited for proving instrumentation concepts.

7.4 NOAA ETL

The National Oceanographic and Atmospheric Administration's Environmental Technology Laboratory in Boulder, Colorado, is a pioneer developer of remote-sensing systems for detecting atmospheric phenomena using radar, microwave radiometers, and RASS. ETL has developed some of the finest research radars and radiometers available and has played an important role in several icing research programs, such as the 1989–1994 Winter Icing and Storms Project in Colorado, and the 1999 Mt. Washington Icing Sensors Project in New Hampshire. ETL often partners with NCAR in atmospheric research and will play an important role in atmospheric characterization and remote-sensing technology development.

7.5 Department of Defense

Aviation has been the nation's first line of defense for 50 years. Each of the military services operates a fleet of aircraft best suited to their mission requirements. Only the Army, however, directly addresses cold-weather problems because of its close association with winter weather conditions on and near the ground. The Army's Cold Regions Research and Engineering Laboratory has taken the DoD lead in developing remote-sensing systems for avoiding aircraft icing conditions. Working hand in hand with NASA and the FAA, CRREL is assisting in the management and development of icing avoidance capabilities to improve military readiness.

8.0 IMPLEMENTATION

Two tasks are involved in the implementation of a remote-sensing ice-avoidance capability for aviation. The first is the development of a coherent and cooperative research and development plan, led by the federal government but coordinated with industry and universities. The second is development of requirements, either voluntary or mandated, by the FAA to place remote-sensing systems at airports or aboard aircraft, as is now common with weather-avoidance radar and wind shear alert, collision-avoidance, and terrain-avoidance systems.

Research and development must be led by the federal government. The government is mandated the responsibility of enforcing aviation safety, and it has the public trust. Development of icing avoidance capability with onboard remote sensors is a high-risk venture that is not likely to be undertaken by industry. In addition, the White House Commission on Aviation Safety and Security requires that the government take a leadership role in improving aviation safety. Weather, including icing, is related to roughly 27% of all general aviation accidents and 33% of all commercial aviation accidents. In response to accidents, the FAA Inflight Aircraft Icing Plan was developed. The NASA Aviation Safety Program was also implemented in response to the report of the White House Commission on Aviation Safety. The Department of Defense is responding to a need to improve military safety and readiness.

The result is a need for federal leadership and coordination in the development and implementation of a capability for remotely detecting and avoiding in-flight icing conditions. In response, NASA, the FAA, and CRREL have signed cooperative agreements to assess the need and encourage the development of a remote-sensing capability. This report supports that goal.

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APPENDIX A: SYNOPSIS OF OPERATIONAL INFORMATION NEEDS, STATE OF KNOWLEDGE, STRENGTHS, AND WEAKNESSES

INFORMATION NEEDS

Pilot needs and human factors

1. Determine pilot information needs.
2. Design information displays conducive to effective risk assessment and cockpit resource management.
3. Understand pilot decision-making process for accurate hazard/risk assessment.
4. Develop avoid/escape strategies.
5. Determine effect of aircraft performance on avoid/exit strategies vs. information needed.
6. Determine an acceptable warning lead time.
7. Determine optimal training requirements.
8. Develop unambiguous indications of icing, and an ability to sense through icing.
9. Improve operational guidelines for flight in icing.

Operators and manufacturers

1. Minimize remote-sensing system cost, size, power, and weight and maximize maintainability, simplicity, and reliability.
2. Establish aircraft space, weight, and power equipment constraints.
3. Develop incentives to use in-flight remote-sensing icing-avoidance systems.
4. Establish aircraft operational limits in icing.

Regulatory issues, weather forecasting, and traffic management

1. Establish aircraft icing performance limits.
2. Develop simple, scientific, standardized scale for reporting icing potential.
3. Develop regulatory operational concept and functional requirements.
4. Develop training standards and requirements.
5. Develop clear, unambiguous guidelines of when severe icing conditions are entered.
6. Consider status of remote-sensing information—whether it should be an advisory or warning system.
7. Create incentives for operators and manufacturers to install remote-sensing systems.
8. Expand FAR 25, Appendix C, to include freezing drizzle.
9. Develop ground-based icing remote-sensing systems for terminal areas.
10. Create regulatory policy development plan.
11. Consider system integration, protocol compatibility, and certification.
12. Determine impact on NAS, ATC, and Free Flight.
13. Develop standards to integrate ground, in-situ, and remotely sensed information.
14. Develop auto-reporting standards for ground (ATC and weather) and other-aircraft linkages.
15. Develop testing standards for remote-sensing systems.

Test beds and platforms

1. Develop training and simulation protocols.
2. Locate test beds and platforms for sensor, information, avoidance, and escape procedure testing.
3. Develop testing standards.

STATE OF KNOWLEDGE

Pilot needs and human factors

1. Pilots have no indication when they are in icing conditions that exceed aircraft limitations.
2. Pilots often do not know how to avoid or escape icing.
3. Pilots want to know if icing conditions lie ahead.
4. The stated icing information needs of a few pilots, and of ALPA pilots as a union, are known.
5. Pilot reports are weak; spatial, temporal accuracy, and terminology standardization are lacking.
6. It is known how pilots use weather radar and wind shear alert systems, which may serve as analogs.
7. It is known how information displayed affects pilot reaction to terrain and wind shear alerts.
8. An effective icing display needs to be designed.
9. Pilots want a simple icing display, but other information may be needed because of airframe and mission differences.
10. Avoid/exit strategies should be identified and tested—perhaps in a simulator.
11. Effects of aircraft performance on avoid/exit strategies and on information needs by pilots are not known.
12. Limitations of aircraft performance in avoid/escape strategies are known through experience.
13. Pilots do not know aircraft limits in icing.

Operators and manufacturers

1. Reliability, cost, size, power, and weight estimates for remote-sensing systems can be estimated, though poorly, from existing onboard systems.
2. Room, power available, and weight allowable for remote-sensing systems are unknown for most aircraft, except when newly delivered from manufacturers. After aircraft delivery, operators may provide information.
3. Simplicity, maintainability, and reliability of icing remote-sensing systems are currently unknown except for extrapolation of records from other weather-avoidance sensors.

Regulatory issues, weather forecasting, and traffic management

1. Operating limits of aircraft in icing conditions outside of FAR 25, Appendix C, are not known.
2. Information needed to create a standardized icing potential scale is available.
3. An operational concept of a remote-sensing icing-avoidance system needs further development.
4. Functional requirements of remote-sensing icing-avoidance system need development.
5. Regulations currently do not address icing conditions beyond conditions defined in FAR 25, Appendix C.
6. There is little incentive for operators to place an icing remote-sensing system on aircraft.
7. There are no ground-based icing remote-sensing systems, though they are under development.
8. There is no regulatory policy with regard to remote-sensing icing-avoidance systems. However, onboard weather radar and wind shear alert systems are analogs for aircraft-based systems, and ground-based wind shear alert systems are analogs for ground-based icing-avoidance systems.
9. Remote-sensing icing-avoidance systems may complicate Free Flight and ATC operations in terminal areas.
10. Weather forecasters do not have reliable indications of icing conditions. Only pireps provide information, which is often inaccurate as to position, time, and intensity.
11. Weather forecasters know the information they want to improve icing forecasts.
12. Integrating aircraft and ground information is not well understood, though some work is being done in the AGATE program.
13. Integration of in-situ, remote-sensing, and ground information may be difficult because of spatial and temporal inconsistencies.
14. Reporting remotely sensed information to other aircraft may require processing through a ground station. This would be more difficult for military aircraft, which may not be able to benefit from such services.

Experimental test beds

1. Experimental test beds for training and development of avoid/exit procedures could be developed using flight simulators.
2. Test beds for air traffic control and pilot training are needed.

OPERATIONAL INFORMATION KNOWLEDGE

Strengths

1. General operational concept of icing remote-sensing system.
2. General ideas of pilot information needs.
3. Use of current onboard radar and wind shear alert as analogs.
4. Use of remote-sensing systems in regulated air space.
5. Information display problems from radar and wind shear alert systems.
6. Weather information needed by meteorologists.

Weaknesses

1. Lack of standardized, objective icing rating terminology.
2. Unknown limits of aircraft capabilities in icing conditions outside Appendix C.
3. Poor knowledge of how to avoid and escape icing.
4. Lack of incentives for manufacturers and operators to use remote-sensing systems.
5. Definition of beyond FAR 25, Appendix C, conditions.
6. Undeveloped functional requirements (specifications) of a remote-sensing icing detection system.
7. Use of remote-sensing systems in Free Flight.
8. Development of effective display for icing conditions.
9. Effects of aircraft performance on avoid/exit strategies and information needs.
10. Location of effective experimental test beds for pilots, air traffic controllers, and meteorologists.
11. Reliability, cost, size, power, and integration into airframe.
12. Quality and type of information that will be provided to meteorologists and ATC from remote-sensing systems.
13. Regulatory hurdles.
14. Integration of ground, in-situ, and remotely sensed information.
15. Training standards.

16. Establishing pilot needs.
17. Establishing remote-sensing system range, scan rate, resolution, and warning time to meet pilots' needs.

GENERAL GOALS

1. Assess the needs of a greater variety of pilots. Study information needs of pilots in greater cross-platform/cross-mission variety. For example, ALPA, military, helicopter vs. turboprop vs. jet vs. general aviation.
2. Investigate pilot decision-making process. Investigate what information, to what distance, resolution, and detail and types of displays pilots need.
3. Investigate concerns and limitations of airframe manufacturers.
4. Investigate operator needs and limitations.
5. Develop specifications for remote-sensing system.
6. Investigate information dissemination problems—to ground, to other aircraft, information needed by ground, information aircraft can provide (remote and in situ).
7. Investigate feasibility of using simulation to develop pilot interfaces, and avoid-and-exit strategies.
8. Investigate integration of remotely sensed and in-situ measurements for assessing proximity to aircraft operational limits.
9. Develop simulation and training aids.

APPENDIX B: SYNOPSIS OF SENSING NEEDS, STATE OF KNOWLEDGE, STRENGTHS, AND WEAKNESSES

SENSING NEEDS

Characterization

1. Good climatologies of icing conditions in all synoptic situations.
2. Synoptic, continental, and global icing patterns to determine system utility.
3. Fully characterize supercooled large droplet climatology.
4. Characterize liquid-water content, drop size, and temperature conditions in all icing synoptic situations.
5. Determine the variability of cloud characteristics (such as liquid-water content, droplet size, and temperature) within 3-D space (vertical and horizontal).
6. MVD or equivalent may not be acceptable because they poorly represent “nonstandard” (i.e., non-Gaussian) distributions of drop sizes observed in clouds with drizzle drops.
7. Drop-size distributions are often not correctly represented by current instrumentation, and ice crystals or drops can confuse sensing systems. Better instrumentation is needed.
8. More research flights specifically planned to measure information needed to characterize the icing environment with regard to remote-sensing systems—with better instrumentation.
9. Rework existing flight data.
10. Measure cloud microphysical properties and resulting ice on aircraft with in-situ sensing systems to calibrate remote-sensing system dynamically.
11. Improve characterization of freezing rain aloft.
12. Characterize droplet temperature variations.
13. Characterize mixed-phase clouds with temperature.

In-situ instrumentation

1. In-situ instruments with better dynamic range and sensitivity.
2. Small, accurate, and inexpensive in-situ technologies.
3. Improved SLD measurement instrumentation.

General

1. Determine what characteristics of clouds are critical to flight from flight tests, tunnel tests, and numerical models, in a spectrum of meteorological conditions from a wide variety of aircraft.
2. A meteorology-based icing intensity standard.
3. Determine the critical technical capabilities for a remote-sensing system, such as range needed to observe through most icing conditions, scanning rate/resolution, accuracy. Information needed is primarily meteorological, but also operational.
4. Weather forecasters and numerical models need downlinked objective, timely temperature, liquid-water content, and drop-size information that is accurate in position.

STATE OF KNOWLEDGE

Characterization

1. 3-D organization of icing patches is poorly understood with regard to usefulness of a remote-sensing system.
2. Range and scale of liquid-water content, drop size, and temperature variability is not well understood in 3-D space, especially at the submesoscale, and especially for supercooled large drops.
3. Climatology of supercooled large drops is poorly understood.
4. Submesoscale, continental, and global scales of aircraft icing are poorly understood.
5. Drop-size distributions are not well characterized by current instrumentation—especially for larger drops.
6. Ranges of liquid water content are reasonably well understood, but not in relation to drop size and temperature.
7. Synoptic scale of icing is reasonably well understood.
8. General climatologies of aircraft icing exist and are reasonably well understood.
9. Research flight information exists that can be reanalyzed at little cost for better characterization.
10. Characterization of freezing rain and freezing drizzle aloft poorly understood.
11. Characterization of temperature poorly understood.

In-situ instrumentation

1. Accuracy and dynamic range of in-situ instruments need improvement, especially for SLD.
2. Small, accurate, and inexpensive in-situ instruments are unavailable.
3. 3-D remote-sensing resolution, range, and angular scanning area need specification.
4. Characteristics of clouds critical to flight in icing on many airframes in many conditions are poorly understood.

General

1. We can currently only speculate about the ideal remote sensor scanning range needed—distance and angular, accuracy, and 3-D sensing resolution needed.
2. There is no index of icing conditions by intensity as a function of weather condition alone, independent of aircraft type.
3. Characteristics of clouds critical to flight from flight tests, tunnel tests, and numerical models, in a spectrum of meteorological conditions from wide variety of aircraft, are not available.
4. There is no objective system for reporting icing potential independent of aircraft type.
5. There is currently no objective system of reporting areas of icing or no icing that is accurate in intensity, position, and time.
6. Weather forecasters and numerical models currently do not have available objective, timely temperature, liquid-water content, and drop-size information that is accurate in position.
7. A meteorology-based icing intensity standard is needed.
8. Need to expand FAR 25, Appendix C to include SLD.

SENSING REQUIREMENTS KNOWLEDGE

Strengths

1. General climatologies of icing are available.
2. Information desired to be downlinked to forecasters is known.
3. There is considerable data and confidence in FAR 25, Appendix C, icing-condition characterization.
4. General research instrumentation is generally adequate.
5. Appropriate test platforms are available.

Weaknesses

1. Characterization of the 3-D scale of cloud physical properties at the submesoscale, continental, and global scales, including temperature, liquid-water content, and drop sizes.
2. Characterization of SLD.
3. Accurate, reliable, inexpensive in-situ instrumentation.
4. There is no objective, weather-based icing index.
5. Further testing of airfoils needed under a variety of weather and operating conditions.
6. Specifications must be developed for remote-sensing systems.
7. Characterization of test beds needed.
8. FAR 25, Appendix C, must be extended.

General goals

1. Define conditions within which clouds are mixed phase, that is, have ice crystals, because mixed-phase situations indicate that supercooled liquid water exists.
2. Characterize 3-D spatial scales of icing by icing potential and microphysical properties.
3. Assess continental-scale and global-scale icing patterns, frequencies, and intensities to determine needs for commercial aviation and military aviation in potential operational theaters.
4. Characterize SLD conditions with regard to frequency, range of conditions, synoptic situations, and continental and global patterns.
5. Reanalyze old flight data with improved instrument-correction algorithms.
6. Fly new research flights to develop specifications for remote-sensing systems.
7. Develop small, turnkey, inexpensive in-situ instruments for aircraft.
8. Investigate feasibility of dynamically calibrating remote-sensing systems from in-situ sensors.
9. Develop sensing specifications for remote-sensing systems.
10. Develop meteorologically indexed icing intensity scale.
11. Assess synoptic meteorological conditions within which remote sensing would be most practical.
12. Identify appropriate test beds.

APPENDIX C: SYNOPSIS OF SENSOR TECHNOLOGY NEEDS, STATE OF KNOWLEDGE, STRENGTHS, AND WEAKNESSES

SENSOR TECHNOLOGY NEEDS

1. Establish sensing needs for phenomena to be sensed, including range and resolution.
2. Develop inversion theory to determine most appropriate technologies for sensing 3-D spatial structure of liquid-water content, drop-size spectra, and temperature ahead of aircraft.
3. Develop prototype hardware for testing theory for each selected component of remote-sensing system.
4. Select test bed for proving concepts developed in theory, develop test plans, and test.
5. Develop airborne prototype system component prototypes.
6. Test airborne prototypes on flight platform and verify capabilities.
7. Develop integrated system comprising all components, with processing and display system compatible with onboard systems and protocol.
8. Test integrated prototype system on civilian and military flight platforms.
9. Certify system.

STATE OF KNOWLEDGE

Radar

1. Ground (vertical scanning) and airborne (horizontal scanning) systems are technically possible.
2. Range-resolved liquid water measurements have been acquired from clouds.
3. Polarization techniques can be used to detect ice vs. water.
4. Doppler techniques to detect droplet sizes may not be possible with horizontally scanning systems.
5. Longer wavelengths (lower frequencies) cannot detect smaller droplets but have longer range and can operate within Rayleigh regime to larger drop sizes. Useful for detecting precipitation.
6. Shorter wavelengths (higher frequencies) detect smaller drop sizes but have shorter range and cannot operate within Rayleigh regime in larger drops.
7. Differential attenuation of two or more radar wavelengths allows liquid-water content to be retrieved.
8. Millimeter-wavelength radars most suited for cloud-water sensing.
9. Wider ranges of drop sizes in precipitating clouds increase the need for a multiple-wavelength (more than two) radar system.
10. Differential attenuation techniques may require droplet temperature for accurate assessment of liquid-water content.
11. Gossett and Sauvageot (1992) theoretically demonstrated that 3.2-cm (X) and 0.87-cm (K_a) bands are the best for detecting water in clouds, but that other wavelength pairs are possible, depending upon desired range and the existence of hydrometeors.
12. Millimeter-wavelength radars are suited to airborne cloud studies because of their small size, low ground-clutter susceptibility, high resolution, and sensitivity to small hydrometeors.
13. It may not be possible to uniquely define cloud drop-size distributions with radar. Only parameters of a distribution may be available.

Passive radiometers

1. Operationally used to measure zenith and nadir temperature profiles, with thermal and spatial resolution decreasing with distance from radiometer.
2. Integrated liquid-water path sensed in vertical at 31.6 GHz with scanning possible.
3. Integrated liquid water might be sensed in horizontal to provide integrated water that an aircraft could intercept.
4. Modeling and experiments needed at test beds.
5. Precipitation can cause difficulties—modeling is needed.
6. Cloud phase may be possible with polarimetry.
7. Scanning liquid-water radiometer under development provides range resolution.
8. Passive technology advantage for cost, size, weight, power, general aviation, and military applications.
9. Model with RADTRAN or its successors.
10. Radiometer scanning is slow.

Lidar

1. Scatter proportional to number density of drops.
2. High spatial resolution.
3. Multiple-field-of-view lidars can indicate effective drop diameter, but distribution must be assumed.
4. Liquid-water content can be measured.
5. Can estimate relative amount of ice crystals from amount of polarization.
6. Current MFOV lidars not eye-safe, but could be at 1.54 or 2.0 µm with 1.5- to 3-m resolution.
7. Could be placed on an aircraft.
8. Detect to clouds through clear air, but cloud extinction allows only few hundred meters penetration.

Temperature measurements

1. RASS profiles temperature to radiosonde accuracy to over 3.5 km, even inversions.
2. RASS has not been used on moving vehicles or in the horizontal.
3. Pitch, roll, and yaw and aircraft speeds prevent RASS use on aircraft.
4. RASS acoustic source could be aircraft engine noise, but turbulence and relative wind could cause loss of signal for up to 1 min depending upon aircraft speed and heading.
5. Radiometers may sense temperature in horizontal. Might try tunable system operating in the vicinity of the oxygen absorption band, with tuning providing range resolution.
6. Radiometers provide lower-resolution vertical temperature profiles.
7. Lidar not applicable.

TECHNOLOGY KNOWLEDGE STRENGTHS

Radar

1. Ground (vertical scanning) and airborne (horizontal scanning) systems are possible.
2. Successful attempts have been made to acquire range-resolved liquid water from clouds.
3. Polarization techniques can be used to detect ice vs. water.
4. Millimeter-wavelength radars are suited to airborne cloud studies because of their small size, low ground-clutter susceptibility, high resolution, and sensitivity to small hydrometeors.
5. Radar scans rapidly.

Passive radiometers

1. Operationally used to measure zenith and nadir temperature profiles, and possibility in horizontal.
2. Integrated liquid-water path sensed in vertical with scanning possible.
3. Cloud phase may be possible with polarimetry.
4. A scanning liquid-water radiometer under development provides range resolution.
5. Passive technology has an advantage for cost, size, weight, power, general aviation, and military applications.
6. Model with RADTRAN or its successors.
7. Radiometers can be small and use little power.

Lidar

1. Pulses can be only 2 to 3 m long, yielding very high spatial resolution.
2. Multiple field-of-view lidars can indicate effective drop diameter and liquid water content.
3. Can retrieve relative amount of ice crystals from amount of polarization.
4. Multiple field-of-view lidars could be eye safe at 1.54 or 2.0 mm with 1.5- to 3-m resolution.
5. Five-watt power demand, 6- to 8-in. receiving lens, 100 pulses s^{-1}, 1-m^3 volume, could be placed on an aircraft.
6. Lidar currently used for operational onboard wind shear alert.
7. Small and inexpensive.
8. Rapid scanning possible.

Temperature measurement

1. RASS sounds temperature with radiosonde accuracy, even through inversions.
2. Radiometers are used operationally to create vertical temperature profiles.
3. Radiometers may sense temperature in horizontal. Might try tunable system operating in the vicinity of the oxygen absorption band, with tuning providing range resolution.

TECHNOLOGY KNOWLEDGE WEAKNESSES

Radar

1. Doppler techniques to detect droplet sizes not possible with horizontally scanning systems.
2. Wider ranges of drop sizes in precipitating clouds, for example, increases the need for a multiple-wavelength (more than two) radar system.
3. Dual-wavelength differential attenuation techniques require temperature for accurate liquid-water content.
4. Gossett and Sauvageot (1992) theoretically demonstrated that X and K_a bands are the best for detecting water in clouds, but that other wavelength pairs are possible. Modeling is needed.
5. It may not be possible to uniquely define cloud drop-size distributions with radar.
6. Dual-frequency radar at X and K_a bands cannot detect small drop diameters to a long range, nor

liquid-water content smaller than 0.2 g m^{-3} (Martner at al. 1993)

7. W-band radar (95 GHz) may be suitable but with short range and great attenuation by large liquid-water content, large drops, and water vapor. Modeling is needed.

Passive radiometers

1. Liquid water might be sensed in horizontal to provide integrated water that an aircraft might intercept.
2. Temperature cannot be sensed in horizontal using conventional inversion methods.
3. Modeling and experiments needed at test beds.
4. Precipitation can cause difficulties at some wavelengths; modeling is needed.
5. Cloud phase cannot be detected with polarimetry.

Lidar

1. High extinction in clouds.
2. Eye safety.

Temperature measurement

1. RASS is operational from the ground and has not been used on vehicles or in the horizontal.
2. Pitch, roll, and yaw and aircraft speed prevent RASS use on aircraft.
3. Radiometers cannot sense temperature in horizontal using traditional inversion methods.
4. Radiometers scan slowly.
5. Lidar not applicable.

General goals

1. Perform feasibility studies of ability of technologies to provide liquid-water content, drop size, and temperature information needed.
2. Develop methods of assessing feasibility studies through measurements with hardware.
3. Develop prototype technologies for field testing.

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13. ABSTRACT *(Maximum 200 words)*

Remote-sensing systems that map aircraft icing conditions in the flight path from airports or aircraft would allow icing to be avoided and exited. Icing remote-sensing system development requires consideration of the operational environment, the meteorological environment, and the technology available. Operationally, pilots need unambiguous cockpit icing displays for risk management decision-making. Human factors, aircraft integration, integration of remotely sensed icing information into the weather system infrastructures, and avoid-and-exit issues need resolution. Cost, maintenance, power, weight, and space concern manufacturers, operators, and regulators. An icing remote-sensing system detects cloud and precipitation liquid water, drop size, and temperature. An algorithm is needed to convert these conditions into icing potential estimates for cockpit display. Specification development requires that magnitudes of cloud microphysical conditions and their spatial and temporal variability be understood at multiple scales.The core of an icing remote-sensing system is the technology that senses icing microphysical conditions. Radar and microwave radiometers penetrate clouds and can estimate liquid water and drop size. Retrieval development is needed; differential attenuation and neural network assessment of multiple-band radar returns are most promising to date. Airport-based radar or radiometers are the most viable near-term technologies. A radiometer that profiles cloud liquid water, and experimental techniques to use radiometers horizontally, are promising. The most critical operational research needs are to assess cockpit and aircraft system integration, develop avoid-and-exit protocols, assess human factors, and integrate remote-sensing information into weather and air traffic control infrastructures. Improved spatial characterization of cloud and precipitation liquid-water content, drop-size spectra, and temperature are needed, as well as an algorithm to convert sensed conditions into a measure of icing potential. Technology development also requires refinement of inversion techniques. These goals can be accomplished with collaboration among federal agencies including NASA, the FAA, the National Center for Atmospheric Research, NOAA, and the Department of Defense. This report reviews operational, meteorological, and technological considerations in developing the capability to remotely map in-flight icing conditions from the ground and from the air.

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