BATTLESPACE FORECASTING OF AVIATION ICING HAZARDS

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ABSTRACT

Aircraft icing endangers aviators, restricts surveillance opportunities, and reduces combat effectiveness. During freezing conditions, clouds and precipitation can contain appreciable amounts of subfreezing liquid water. Aircraft traversing these clouds accumulate ice as supercooled liquid freezes to the wings and airframe. Ice accretion can be very rapid compromising the aerodynamics of the wings and propellers, as well as adding weight and increasing drag.

Advanced warning of weather hazards posed by existing and impending meteorological conditions would allow commanders and aviators to develop mitigation strategies. The resolution and accuracy of forecast of in-flight and ground icing are currently limited by a lack of data on cloud and precipitation phase (liquid or ice), cloud temperature, and cloud droplet or raindrop size. Active systems such as short-wavelength radars, lidars, and passive sensors such as microwave radiometers and in-situ meteorological probes can provide these data. These sensors can be packaged into lightweight, compact, low-power units that could be deployed on the ground or on airborne platforms. When coupled with state-of-the-art retrieval algorithms, these sensors would improve the reliability and timeliness of regional weather forecasts. It is even feasible to develop an integrated field system for forecasting in-flight and ground aviation icing hazards.

INTRODUCTION

In-flight and ground aircraft icing presents a serious hazard for military aviation. Improved forecasting capability would provide important tactical and strategic advantages during mid-latitude winter and year-round polar operations. The ability to accurately forecast icing hazards is an essential component in enhancing safety and mission effectiveness during in-flight and ground icing conditions.

Aviation hazards can be managed with information. Improvements in the capability to characterize clouds and precipitation will lead to improvements in the reliability and effectiveness of icing forecasts and nowcasts [*Stack*, 1996; *Ryerson*, 1996]. The techniques needed to achieve an advanced level of cloud sensing capability have already been developed. In fact, many of the technologies have been used in icing research for more than a decade. Implementing improvements in cloud and precipitation detection, identification, and characterization are essential for advancing current measurement capabilities beyond the use of these data to mitigate the effects of adverse weather. In the future, this capability will allow weather to be exploited to obtain a strategic advantage.

ICING METEOROLOGY

Freezing rain and freezing drizzle are usually responsible for creating ground and in-flight icing conditions. A frequent scenario for generating freezing precipitation occurs when rain falls from a warm zone into an underlying subfreezing region. [*AOPA*, 1994] These conditions are common near the edge of a cold front. As liquid precipitation traverses the subfreezing region, it supercools, but does not freeze due to the lack of condensation nuclei. Icing conditions are also common in winter storms where there is a boundary separating frozen precipitation (snow) from liquid precipitation (rain) as illustrated in Figure 1. Non-precipitating clouds also can pose serious icing hazards. Rapid cooling of cloud liquid near the border of a front can also create large reservoirs of supercooled liquid. It is the presence of supercooled liquid that poses a threat to aircraft.

The hazard associated with freezing precipitation and supercooled cloud liquid is a function of the liquid density, drop size distribution, ambient temperature, and aircraft-specific characteristics. The abundance of supercooled liquid water is usually the most important parameter for forecasting icing hazards. Liquid density determines the reservoir of liquid available for accretion. [*AOPA*, 1994]. Drop size also affects the level of hazard. Large droplets (droplets with diameters > 50 µm) are more likely to flow backward along the wing where they can freeze aft of ice protection systems [*Al-Khalil*, 1996].

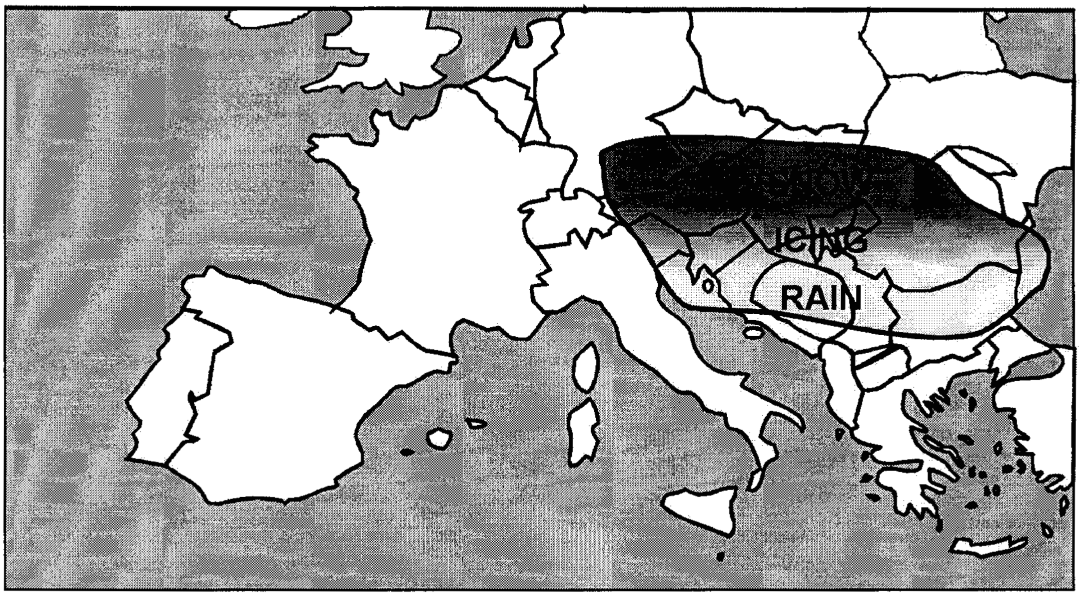

Figure 1. *In-flight and surface icing conditions often occur in a winter storm's transition zone that separates the region of snowfall from the region of rain.*

AVIATION HAZARDS

Ice accretion primarily affects aircraft performance by changing the aerodynamics of the wings and propellers. Icing also increases the weight of the airframe, increases drag, and can disable control surfaces. On occasion, ice being shed from the airframe can impact and damage adjacent aircraft structures. The rate at which ice accumulates depends on meteorological conditions and aircraft-specific characteristics. The exposure duration is an important factor in assessing the severity of the hazard because lengthening the exposure time increases the mass of accreted ice.

Aircraft that tend to fly at lower altitudes where icing conditions occur most frequently and also tend to operate close to their performance margins are most susceptible to icing. These classes of aircraft include helicopters, piston-engine airplanes, turboprops, and remotely piloted vehicles. Smaller aircraft and helicopters are often not certified to fly in icing conditions and are therefore not equipped with deicing systems. This puts them at greater risk when they encounter unforecasted icing conditions. Ryerson [1996] provides a brief review of the effect of icing on military air operations.

SENSOR TECHNOLOGY

The choice of sensors requires a systems analysis. Issues affecting a sensor's selection include its contribution to the existing meteorological network, technological maturity, suitability for the intended platform, and its affect on other military systems. In-situ sensors directly sample local meteorology, while remote sensors probe meteorological properties at a distance. Microwave remote sensors usually have an advantage over optical sensors because they can penetrate optically thick clouds and precipitation. Remote sensors can be categorized as active sensors that emit signals and then measure their interaction with the environment and passive sensors that measure natural radiation emitted by the environment. Although active systems usually provide the most complete characterization of the meteorological environment, they also tend to require more power, are harder to conceal, are more expensive, and are more likely to interfere with other C^3I systems. The choice of sensors requires optimizing system needs, cost, and logistical requirements

Sensors for improving icing forecasts have already been developed [*Stankov et al.*, 1995; *Han and Westwater*, 1995] and many are commercially available. However, there are two areas where targeted research and development would yield significant benefit. Considerable value could be derived from re-engineering the existing research instrumentation. Scientific sensors developed with a design emphasis that maximized capability, accuracy, and operational flexibility should be redesigned with a focus on developing an application-specific design, increasing reliability, improving automation, and reducing cost. R&D is also needed to develop advanced airborne sensors to detect and forecast icing. Commercial airborne sensors currently detect ice formation with acoustic, optical, and impedance probes. The next generation of sensors will likely measure meteorological parameters and estimate the icing rate prior to ice forming on the aircraft. This approach will give aviators additional time to formulate effective avoidance and mitigation strategies.

There are several methods used to measure cloud temperature. In-situ temperature probes measure cloud temperature directly. In-situ probes require transport on an aircraft or balloon and telemetry to downlink the signal. Temperature probes are currently carried on some commercial airplanes and routinely measure the temperature profile near major airports. As an alternative, IR radiometers are often used to retrieve cloud base temperature. They measure the infrared brightness of the cloud base and derive cloud base temperature from the measured radiance.

Atmospheric temperature profiles can be measured in the presence of clouds with microwave radiometry, radio-acoustic sounding, and in-situ measurements. A microwave radiometric temperature profiler is a sensitive radio receiver tuned to the 60 GHz emissions of molecular oxygen. The radiance of oxygen emissions depends on temperature. Measurements made at several frequencies and elevation angles will yield the temperature profile. Radio acoustic sounding systems (RASS) are active sensors that transmit a powerful acoustic pulse and track its upward propagation with a VHF radar. Since the acoustic velocity is a sensitive function of temperature, the temperature profile is retrieved from the acoustic pulse propagation velocity. RASS provides higher resolution than microwave temperature profilers, although they are much more expensive, noisy, and require orders of magnitude more power and area to operate. RASS are not easily adaptable to airborne platforms, whereas airborne radiometers are routinely used on NASA aircraft to profile temperature.

Cloud temperature is retrieved from the temperature profile with a simultaneous determination of cloud altitude using a Ka-band radar, lidar, ceilometer, or in-situ sensor. While a lidar is a laser radar, a ceilometer is a simple lidar designed to measure only vertical cloud base altitude. High-power lidars can penetrate multiple cloud layers. However, Ka-band radars are often preferred because they can penetrate much thicker clouds with comparable signal power. In-situ balloon-borne, capacitive and resistive humidity sensors are routinely used to identify cloud height. Detecting cloud height with in-situ humidity sensors has limited utility because it infers cloud occurrence from humidity. This creates a bias because the humidity at which clouds form and sublimate spans a range of humidities and therefore can not be accurately predicted using a humidity threshold [*Gaffen and Elliott*, 1993].

Dual polarization radars, lidars, and microwave radiometers can determine cloud phase (ice or liquid). Polarization sensitive measurements discriminate between ice and liquid hydrometeors by providing sensitivity to the scattering particle height-to-width aspect ratio. As an ice crystal melts, its aspect ratio changes, altering the ratio of reflection cross-sections at each orthogonal polarization. Since radar reflectivity depends on both drop size and total water content, single-frequency radars, alone, are unable to independently determine liquid content. However, research is underway to develop the use of dual-frequency radars to retrieve liquid content [*Reinking et al.*, 1996]. Lidars are limited in range due to hydrometeor-induced attenuation. Liquid-sensing microwave radiometers are sensitive radio receivers tuned to the continuum emissions of liquid water in the 30 GHz and/or 90 GHz atmospheric windows. The radiance of a cloud is proportional to the columnar liquid content. Microwave radiometers can discriminate between ice and water because the dielectric constant of ice is two orders of magnitude smaller than that of liquid and is therefore "transparent" to the radiometer. Thus, clouds or precipitation that emit significant amounts of microwave radiation must contain liquid. Although radiometers do not provide distance information, they have an advantage in some applications because they are passive and much less expensive than radars and lidars. Combining radars and radiometers can be a very powerful strategy because it allows cloud liquid to be profiled [*Stankov et al.*, 1995; *Han and Westwater*, 1995].

In-situ sensors are very effective at determining the phase of precipitation and cloud water. For ground-based applications, rain gauges can differentiate between snow and rain. Supercooled liquid precipitation can be detected with a vibrating wire or rod [*Hill*, 1994]. Supercooled liquid freezes to the wire or rod, thereby changing the vibrating mass. The associated shift in resonant frequency signals the presence of supercooled liquid. Vibrating wires and rods are used in ground-based stations and have been flown on radiosondes.

Characteristics such as drop size and liquid water content can be inferred by combining microwave radiometers with radars. Drop size and liquid water content can also be retrieved using lidars. In-situ instruments are able to resolve the drop-size spectrum and liquid content by measuring the intensity and angular distribution of light scattered by an atmospheric sample [*Lawson and Cormick*, 1995]. Ground-based systems that record light scattering along a short atmospheric path can be used to retrieve information on the drop size distribution and thermodynamic phase by determining the precipitation rate of descent.

Generating a detailed picture of icing-hazards on a regional scale requires a systems approach. Advanced warning of icing hazards requires enhanced surveillance using a variety of measurement techniques from multiple locations. These data need to be rapidly integrated into a regional forecast model. The forecasts, in turn, need to be promptly disseminated to users in a format that highlights possible impacts to air systems, operations, and maneuvers. It is the combination of enhanced surveillance, improved modeling, integrated information systems, and reliable communications that can extend the time available to effectively mitigate the hazard, or avoid it altogether.

CONCLUSIONS

Advanced warning of freezing precipitation and supercooled cloud liquid is needed to improve the safety, reliability, and effectiveness of air operations. This can be achieved by improving the capability of the existing meteorological observational network to characterize clouds and precipitation. Technology exists that can provide a more complete picture of clouds and precipitation such as short-wavelength radars, microwave radiometers, and in-situ meteorological probes. These ground-based and airborne sensors will improve the capability of regional forecast models to provide accurate, timely forecasts of hazards. The resulting improvements in forecasts will provide commanders, aviators, and aviation support functions with additional time to formulate plans to mitigate and possibly exploit impending weather hazards. Additionally, these measurement systems can be engineered to be quite compact and low cost. Integrating autonomous and networked sensors into the meteorological sensor network is an essential strategy for enhancing the accuracy of forecasting aviation icing hazards.

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REFERENCES

Al-Kahlil, K., "The formation of an ice ridge beyond protected regions," *Proc. FAA Int.Conf. on Aircraft In-Flight Icing, Vol. II* (Tech Rep. **DOT/FAA/AR-96/81,II**), p. 285, (1996).

AOPA, "AOPA's Aviation USA," Ed. M. R. Twombly, Aircraft Owners and Pilot's Association, (1994.)

Gaffen, D. J., W. P. Elliott, "Column Water Vapor Content in Clear and Cloudy Skies," *Jour. Of Climate*, **6**, p. 2278, (1993).

Han, Y. and E. R. Westwater, "Remote Sensing of Tropospheric Water Vapor and Cloud Liquid Water by Integrated Ground-Based Sensors," *Jour. Of Atmos. and Oceanic Tech.*, **12** , p. 1050, (1995).

Hill, G. E., "Analysis of Supercooled Liquid Water Measurements Using Microwave Radiometer and Vibrating Wire Devices," *Jour. Of Atmos. and Oceanic Tech.*, **11** , p. 1242, (1994).

Lawson, R. P., R. H. Cormack, "Theoretical design and preliminary tests of two new particle spectrometers for cloud microphysics research," *Atmos. Res.,* **35**, p. 315, (1995).

Stack. D, "In-flight Icing – The Critical Need for Improved Forecasts and Indexing of the Hazard," *Proc. FAA Int.Conf. on Aircraft In-Flight Icing, Vol. II* (Tech Rep. **DOT/FAA/AR-96/81,II**), p. 297, (1996).

Stankov, B., B. Martner, M. Politovich, "Moisture Profiling of the Cloudy Winter Atmosphere Using Combined Remote Sensors," *Jour. Of Atmos. and Oceanic Tech.*, **12** , p. 488, (1994).

Reinking R. F., S. Y. Matrosov, B. E. Martner, R. A. Kropfli, "Differentiation of Freezing Drizzle from Ice Hydrometeors and Freezing Rain with Dual Polarization Radar," *Proc. FAA Int.Conf. on Aircraft In-Flight Icing, Vol. II* (Tech Rep. **DOT/FAA/AR-96/81,II**), p. 331, (1996).

Ryerson, C., "Remote Detection and Avoidance of In-flight Icing," *Proc. FAA Int.Conf. on Aircraft In-Flight Icing, Vol. II* (Tech Rep. **DOT/FAA/AR-96/81,II**), p. 179, (1996).