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N90-20928

THE INFLUENCE OF ICE ACCRETION PHYSICS ON THE FORECASTING OF AIRCRAFT ICING CONDITIONS * +

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ABSTRACT

The physics which control aircraft ice accretion are reviewed in the context of identifying and forecasting hazardous icing conditions. The severity of aircraft icing is found to be extremely sensitive to temperature, liquid water content and droplet size distribution particularly near the transition between rime and mixed icing. The difficulty in measurement and the variability of these factors with altitude, position and time coupled with variable aircraft sensitivity make forecasting and identifying icing conditions difficult. Automated Pilot Reports (PIREPS) are suggested as one mechanism for improving the data base necessary to forecast icing conditions.

1. INTRODUCTION

The accurate and precise forecasting of meteorological conditions favorable to aircraft ice accretion is difficult for several reasons. First, the type and severity of ice accretion is often strongly or nonlinearity dependent on environmental parameters such as temperature, liquid water content, cloud droplet size distribution, turbulence level and water phase. Secondly, several of these parameters are difficult to measure or estimate in the forecasting environment. Finally the severity of the ice accretion and its influence on aircraft performance will depend on both the type and flight condition of the aircraft.

This paper will examine those meteorological and aircraft factors which influence the physics of ice accretion in order to gain some insight into the limitations of current forecasting techniques and the requirements for improved icing forecasts.

2. OVERVIEW OF THE ICE ACCRETION PROCESS

The ice accretion process is controlled by two physically distinct subprocesses. The first is the inertial transport of liquid water (either in the form of cloud droplets, rain drops or mixed phase hydrometeors) from the ambient environment to the aircraft surface. Once droplets have impacted the aircraft surface, their freezing becomes controlled by thermodynamic processes. If the heat transfer from the surface is sufficient to remove all the latent heat of freezing of the impinging water than the droplets will freeze on impact resulting in a dry ice surface. The ice shape typically protrudes forward into the airstream and is commonly referred to as rime ice (see Figure 1).

When the heat transfer from the surface is inadequate to remove all of the latent heat from the impinging droplets the ice surface becomes wet. This type of accretion is commonly characterized as glaze ice. In some cases, both wet and dry ice growth can occur at different places on the same body. This situation is referred to as mixed ice growth. Often in glaze or mixed conditions, the resulting ice shape displays two pronounced growth peaks on either side of the stagnation line (see Figure 1). The most severe aircraft performance degradation is typically associated with such horned ice formations (Renaudo, et al., 1984). Because the physics of mixed and glaze icing are similar, the term mixed icing will refer to both mixed and glaze unless otherwise noted.

The physical processes which control ice accretion are distinctly different for dry and wet ice growth. In dry growth, where the droplets freeze on impact, the ice accretion is controlled by the local rate of impingement of liquid water on the surface. The local impinging mass flux is an inertially determined quantity which involves the individual droplet trajectories as they pass through the flowfield surrounding the body. For wet growth, the ice accretion is controlled by the rate at which latent heat of fusion can be removed from the surface. The heat transfer behavior of the ice surface, therefore, becomes the controlling mechanism for wet ice growth. For mixed icing conditions both the impingement and heat transfer mechanisms play important roles in the ice accretion process.

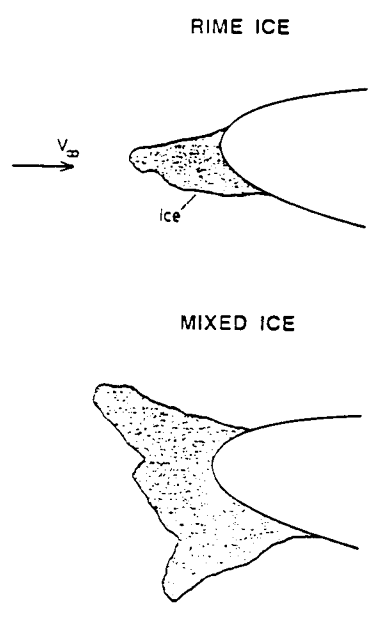

Fig. 1 Typical dry (rime) and wet (mixed/glaze) ice shapes.

2.1 Water Impingement

The physics which control the impingement of liquid water onto the aircraft surface are fairly straightforward. Because the surface is not permeable to gas, flow streamlines do not intersect the body as can be seen in Figure 2. Water droplets have a higher ratio of inertial to hydrodynamic forces than gas molecules and will tend to cross the streamlines resulting in impingement as shown in Figure 2.

* Preprint, Third International Conference on the Aviation Weather System, 1989.
+Some original figures were not available at time of publication.

Much work has been done on droplet impingement trajectories to determine local collection efficiencies β (Bergrun, 1947, Bragg, et al.,1981, Brun, et al, 1953, Gelder, et al, 1956, Hansman, 1984). The local collection efficiency is defined as the fraction of the mass flux locally impinging onto the surface to the freestream mass flux. The collection efficiency is typically highest near the stagnation point of the body and decreases downstream. The point at which β becomes zero is defined as the impingement limit. The collection efficiency is a strong function of droplet size and body geometry. Large droplets have high inertia tending to cross streamlines resulting in high collection efficiencies and impingement limits. Small droplets tend to follow the streamlines resulting in lower collection values. Small bodies are more efficient droplet collectors because there is less room for the droplets to turn prior to impact.

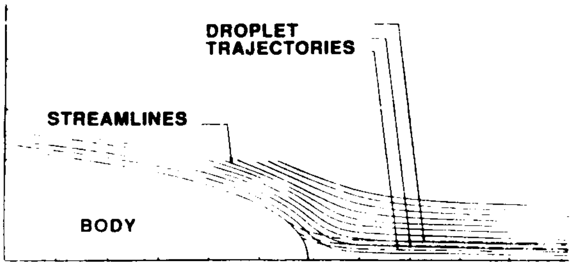

Fig. 2 Example of the relation of water droplet trajectories to the streamline field from Bergrun (1947).

2.2 Thermodynamic Heat Balance

As described above, the thermodynamic heat balance on the accreting ice surface is a controlling factor in determining the rate of ice accretion in mixed icing conditions and is the critical factor in determining the transition between these conditions and rime ice growth. Figure 3 shows the principal modes of energy transfer associated with an icing surface, as depicted by Messinger (1953). Heat is added to the surface primarily from the latent heat of fusion released as the droplets freeze, but also from aerodynamic heating and, to an even smaller extent, from the kinetic energy of the droplets impacting the surface. Heat is removed from the surface primarily by convection, and to a lesser degree by sublimation (when the surface is dry) or evaporation (when the surface is wet). In addition, heat is absorbed from the surface as the supercooled droplets impinge and warm to 0° C. The parameters which primarily influence the heat balance are the temperature difference between the surface and the free stream, the convective heat transfer and the impinging liquid water mass.

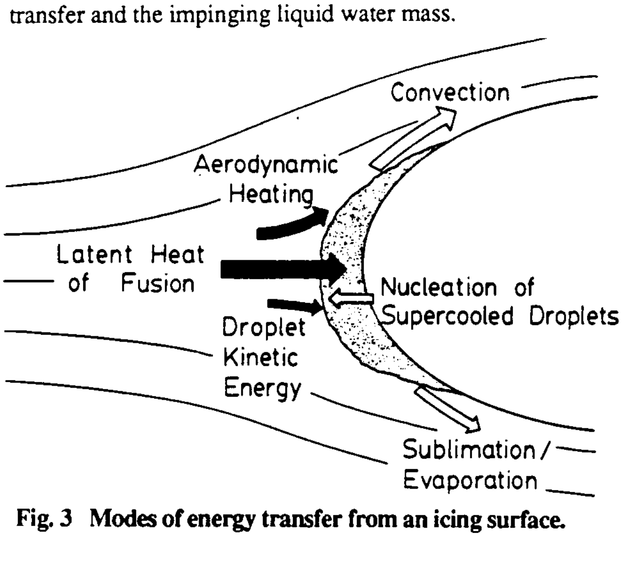

Fig. 3 Modes of energy transfer from an icing surface.

3.0 INFLUENCE OF METEOROLOGICAL PARAMETERS

The influence of various meteorological parameters which are considered important aircraft icing are discussed below in terms of their effect on the physics and the severity of the ice accretion.

3.1 Temperature

Air temperature is one of the most important of the icing parameters. Meteorologists normally work with the ambient or Outside Air Temperature (OAT) however pilots and aircraft designers also use Total Air Temperature (TAT) to include aircraft velocity effects. The TAT is the temperature at the stagnation point of the aircraft and corresponds to the OAT plus an additional temperature rise due to the deceleration of the incoming flow. This "ram rise" can be significant at high velocities. In Figure 4 it can be seen that the difference between stagnation and ambient temperature (TAT-OAT) may be as high as 30° at 500 kts. Because the surface temperature can be lower than the TAT aft of the stagnation point of the aircraft the normal procedure in jet aircraft is to operate anti-icing equipment at TAT values between +10° C and -10° C in the presence of visible moisture.

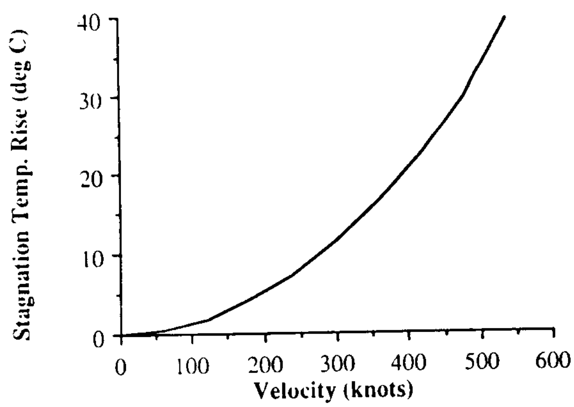

Fig. 4 Stagnation temperature rise versus velocity.

An example of the effect of temperature on ice accretion and performance degradation can be seen in Figure 5. which shows ice shapes and section drag coefficients for a NACA 0012 airfoil at 4° angle of attack obtained by Olsen, Shaw (1984) in the NASA Lewis Icing Research Tunnel. At cold temperatures, the ice accretion was insensitive to temperature and rime accretions were observed with drag increases of 2 to 3 times the clean values. However as the temperature increased above -10° C the drag increased sharply with temperature to a peak value of over 8 times the clean drag. What happened was that the ice growth transitioned from a dry rime growth to a wet mixed growth. The horns characteristic of mixed growth can be observed in the high drag ice accretions. As the Total Air Temperature nears 0° C the ice accretions and the resulting performance degradations decrease due to insufficient heat transfer to freeze all of the incoming water.

From this example it is clear that a relatively small temperature change can cause transition from a relatively benign rime icing condition to a dangerous mixed condition. The nonlinear dependance of icing severity on Total Air Temperature (TAT) combined with aircraft velocity effects make it difficult to accurately identify regions of moderate or severe ice potential from the ambient air temperature alone.

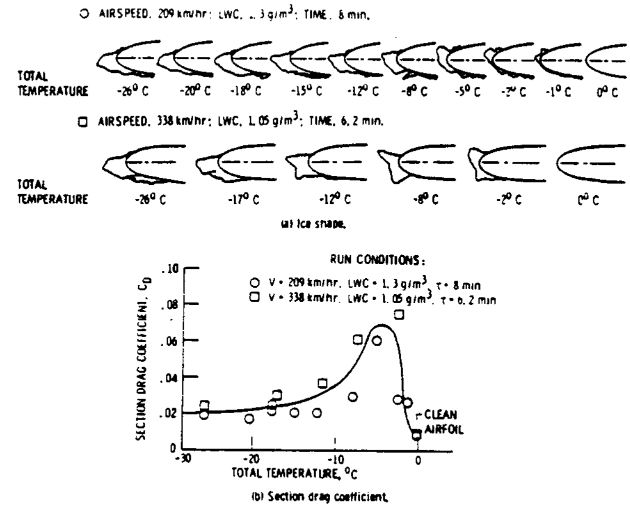

Fig. 5 Effect of total temperature on ice shape and drag. MVD = 20μm; 0.053 m cloud NACA 0012 airfoil at 4° angle of attack. Taken from Olsen, Shaw and Newton (1984).

3.2 Liquid Water Content

Liquid Water Content (LWC) influences the severity of the icing in two primary ways. First, increasing LWC implies more potential water and larger accretions within a given time. Thus, high LWC implies a greater urgency and therefore severity of the icing encounter. The second effect of high LWC is to cause the ice accretion to transition from rime to mixed icing due to the higher impinging water load on the icing surface. This can be seen in the schematic plot of icing severity versus LWC in Figure 6. Rime ice growth will occur even at relatively warm supercooled temperatures for low liquid water contents. In this regime there is a linear increase in the icing severity with LWC. At some value of LWC however, the growth will transition from rime to mixed and the severity of the icing will increase. At colder temperatures the threshold for the transition will occur at a higher liquid water content.

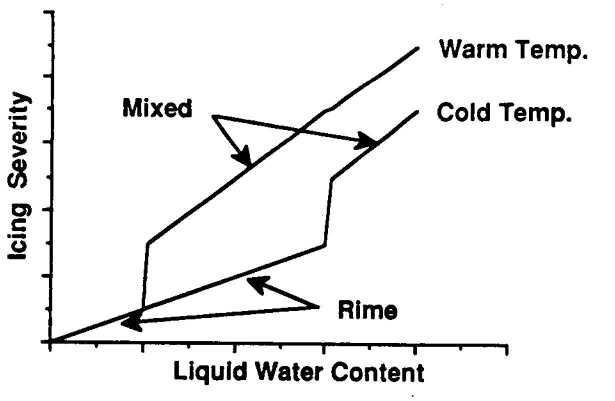

Fig. 6 Schematic plot of icing severity versus liquid water content.

An additional factor which complicates the the ice accretion process is the large variability in LWC often within the same cloud. Figure 7 shows an example of LWC measured by Hansman and Kirby (1987) with a Johnson-Williams hot-wire probe mounted in the nose of the NASA "Twin Otter" Icing Research Aircraft. During this flight, the

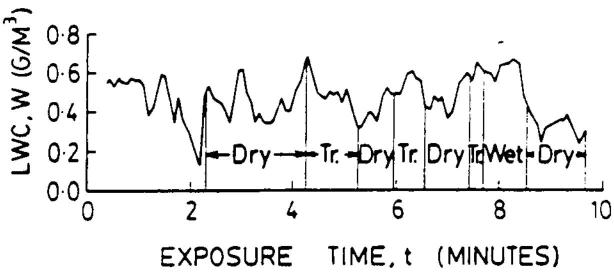

Fig. 7 Plot of liquid water content versus exposure time showing typical fluctuations observed in natural icing conditions. Also shown are ultrasonically measured periods of wet, dry and transitional ice growth.

stagnation point ice accretion was monitored by ultrasonic techniques which could determine weather the accretion was dry, wet or transitional. It can be seen that the variation in liquid water content caused the accretion to vary from dry growth characteristic of rime accretion to wet growth characteristic of mixed accretion within the same cloud.

3.3 Droplet Size

The size of the ambient water droplets both in terms of the Median Volumetric Diameter (MVD) and the actual shape of the Droplet Size Distribution can be important to the ice accretion process. As described in Section 2.1, large droplets are more efficiently caught by body. These effects have been quantified for typical cloud and rain size distributions by Hansman (1984). Figure 8 shows the impinging mass distribution function and the ambient size distribution function for a Khrigian-Mazan distribution with 20 micron mean effective droplet diameter. It can be seen that the bulk of the impinging mass results from the small number of large droplets in the tail of the distribution. The MVD and the shape of the distribution therefore determine the effective collection efficiency of the aircraft. It is not uncommon to have trace or negligible icing even at high liquid water contents for clouds of predominantly small droplets. It is also possible to have moderate to severe icing at relatively low liquid water contents for distributions consisting primarily of large droplets.

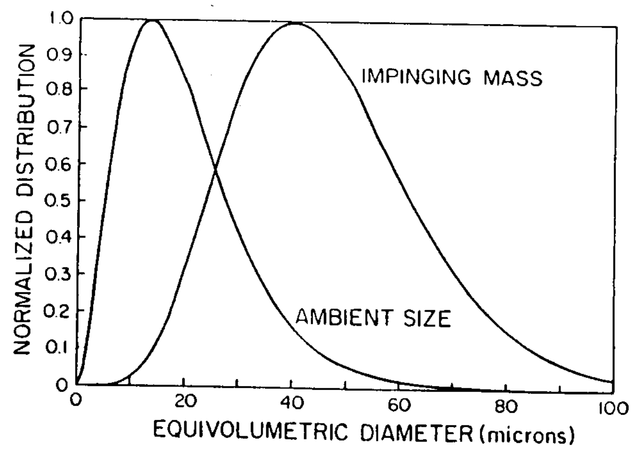

Fig. 8 Khrigian-Mazan ambient cloud droplet size distribution and the resulting impinging mass flux distribution.

The presence of large droplets within the cloud distribution can result in additional hazard due to increased impingement limits. The limit of droplet impingement on an aircraft component increases with droplet size. Current design guidance (FAA AC-20-73, 1971) recommends that a diameter of 40 microns be used to determine impingement limits. The presence of significant numbers of droplets in excess of 40 microns can therefore result in ice accretions occurring behind the protected regions of the aircraft. These factors are thought to contribute to the anomalously high performance degradations observed by Cooper, Sand, Politovich and Neal (1984) in clouds with droplets ranging from 40 to 300 microns.

The problems resulting from large droplets are exacerbated in freezing rain where both large droplet sizes and large liquid water contents are combined. Freezing rain commonly results in clear glaze ice accretions with significant runback icing. It is considered an extremely hazardous condition.

3.4 Cloud Phase

The icing potential for a particular cloud is directly related to the phase of the hydrometeors. As described above, icing normally results from the impact of supercooled water droplets. Dry ice crystals, generally, do not adhere to the aircraft surfaces after impact and are therefore not considered an icing hazard. If however, the ice crystals are wet due to partial melting or the aircraft surface is wet due to de-icing or the recent penetration of a high LWC region then the impinging crystals will stick.

Mixed phase icing (not to be confused with mixed rime/glaze icing) is relatively rare. Some examples of mixed phase icing have however, been observed in flight tests by Gayet, Bain and Soulage (1984) who noted that the presence of snow in supercooled clouds significantly reduced the icing rate. Ice crystal sticking on wet aircraft surfaces was observed during NASA Icing Research Aircraft flight tests of ultrasonic ice detector arrays where the wet aircraft surface was documented by ultrasonic techniques (Hansman, Kirby, McKnight and Humes; 1988).

In general, forecasting efforts are directed towards identifying regions of supercooled cloud. Techniques are available to predict cloud phase in stratiform cloud and glaciation results in overestimation of the icing severity (USAF, 1980). However, in cumuliform clouds, cloud phase uncertainty represents a potential source of error in the forecasting of icing conditions.

3.5 Fine Scale Turbulence Level

An additional factor which has recently emerged as potentially important to the ice accretion process is the fine scale (centimeter and below) ambient turbulence level. The turbulence level is known to strongly influence the convective heat transfer from the icing surface. As shown in Section 2.2, the convective heat transfer is one of the primary parameters in determining the transition between rime and mixed icing with the resulting effect on icing severity. Flight test observations by Hansman and Kirby (1987) observed a wide variability in the parametric threshold between rime and mixed icing. The variability was thought to be due to variations in heat transfer resulting from the ambient turbulence level. While the effect of fine scale turbulence level on icing severity has not been directly demonstrated it may be an additional source of uncertainty in the forecasting process.

4.0 INFLUENCE OF AIRCRAFT PARAMETERS

The influence of various aircraft parameters which are considered important to the icing problem are discussed below in terms of their effect on the physics and severity of the ice accretion.

4.1 Velocity

The aircraft velocity effects both the collection of liquid water and the thermodynamics of the icing process. Increasing velocity results in higher impinging liquid water exposure by increasing both the path swept out by the aircraft trajectory in a give time and the collection efficiency.of the aircraft surfaces. Thermodynamically, the velocity effects the heat load through the increased impinging water mass and through increasing the stagnation point temperature at high velocities. This is shown in Figure 4 where the stagnation temperature rise is plotted as a function of velocity.

4.2 Shape

The shape of the accreting body has a large effect on the local collection efficiency. Generally, smaller bodies are more efficient collectors than larger bodies. Therefore, slender components such as propellers, fan blades and antennas will tend to be the most sensitive to ice accretion. As a result of their high collection efficiencies, windshield wipers or Outside Air Temperature probes are often used by crews to detect icing conditions in flight.

Three dimensional shape effects can also be important for many aircraft components. For example wing sweep commonly results in a spanwise variation of the accretion in mixed icing conditions. This "lobster tail" ice can result in significant performance degradation. It should be noted that current forecasting procedures are based on straight wing propeller driven aircraft (USAF, 1980).

4.3 Aircraft Category

The effect of icing varies significantly with individual aircraft design. While it is beyond the scope of this paper to discuss the icing sensitivity of individual aircraft, the sensitivity of broad aircraft categories will be discussed briefly below.

4.3.1 Turbojet/Turbofan Aircraft

Jet aircraft are considered to be the least susceptible to icing. Jet aircraft normally operate with significant quantities of excess thrust which can be used to offset performance degradation. In addition, the typical flight profile of a jet aircraft is to climb and descend rapidly through the lower troposphere where the icing potential is greatest and to cruise at high altitudes (20,000 ft to 45,000 ft.). Occasionally, Air Traffic Control (ATC) requirements will dictate sustained operation at low altitudes particularly in busy terminal areas. The primary icing hazard to jet aircraft is engine failure due to Foreign Object Damage (FOD). This results from the ingestion of chunks of ice which are shed off of other aircraft components such as engine inlets or in some aircrafts the wings. Therefore, critical regions are normally anti-iced with hot bleed air from the engines to prevent any ice accumulation

4.3.2 Turboprop and Reciprocating Aircraft

There is a tremendous variability in the sensitivity of propeller driven aircraft to icing. Large turboprops tend to be fully ice protected and can operate successfully in regions of high icing potential. Small reciprocating engine aircraft are generally not equipped with ice protection and are not approved for flight in icing conditions. Even light icing conditions are a potential hazard to unprotected aircraft and forecasting uncertainties have the greatest impact on this aircraft category.

Propeller driven aircraft operate at low altitudes where icing potential may exist over the entire flight. The most critical components are generally the propellers because loss of propeller efficiency translates directly into loss of thrust. However, even airframe icing can pose a significant hazard because propeller driven aircraft normally operate at much lower excess thrust margins than jet aircraft. Other hazardous factors include; reduced stability, loss of control authority and reduced visibility due to windshield icing.

4.3.3 Rotorcraft

Helicopter icing has become important during the last decade where helicopter flight in Instrument Meteorological Conditions (IMC) has become more commonplace. Helicopter operations occur almost exclusively at low altitudes where there is significant icing potential. Helicopters are extremely susceptible to icing conditions. Rotor icing simultaneously degrades the lift and thrust efficiency of the vehicle. In addition, helicopters typically operate with very slim power margins and can therefore only tolerate minimal ice accretion. Other hazardous factors resulting from helicopter operations in icing conditions include; blockage of engine inlets, reduced control authority, vibration due to asymmetrical ice load on rotors and reduced visibility due to canopy icing.

5.0 IMPLICATIONS FOR THE FORECASTING OF ICING CONDITIONS

Some of the difficulties in forecasting or identifying hazardous icing conditions are clear from the above. Many of the parameters which were shown to be important to the ice accretion process such as the droplet size distribution and cloud phase are not available to the forecaster. Other parameters, which may be available, such as temperature or liquid water content are nonlinearly related to icing severity. Limitations in accuracy and spatial resolution of these parameters result in over or under prediction of the icing severity. Finally the variable susceptibility of different aircraft types implies that a single icing hazard analysis will result in over or under prediction of the severity for certain aircraft categories.

Given the limitations on the forecasting process, current techniques do a remarkably good job at identifying general regions of potential icing conditions. One of the key indicators which are used to validate or initiate an icing forecast are pilot reports (PIREPS). By actually penetrating the icing environment, aircraft can directly measure the severity of the icing condition. One of the difficulties with PIREPS is that the reports are not well calibrated and the variable susceptibility of aircraft discussed in Section 4.3 must be considered in their interpretation. Another problem is the timely dissemination and generation of PIREPS. Because of other responsibilities, ATC cannot always process PIREPS rapidly which may discourage the voluntary pilot reports.

One potential improvement, which has been implemented to a limited extent,is the automated generation and transmission of PIREPS over digital data links. By the use of onboard ice accretion sensors, automated continuous reporting of the presence or lack of icing conditions could be accomplished. If an adequate fleet of aircraft were so equipped, a significant improvement in the forecasting and identification of hazardous icing conditions could be realized. Other potential technical developments which may improve icing forecasting include: vertical sounders, improved satellite imaging, and improved data synthesis systems such as the PROFS system.

6.0 CONCLUSIONS

The severity of aircraft icing is found to be extremely sensitive to temperature, liquid water content and droplet size distribution particularly near regions of transition between rime and mixed icing conditions. The difficulty in measurement and the variability of these factors with altitude, position and time coupled with variable aircraft sensitivity make forecasting and identifying hazardous icing conditions difficult. Automated Pilot Reports (PIREPS) are suggested as one mechanism for improving the data base necessary to forecast icing conditions.

ACKNOWLEDGMENTS

This work was supported by the National Aeronautics and Space Administration, the Federal Aviation Administration under the Joint University Program for Air Transportation, Grants NGL-22-009-640 and NAG-3-666, and the National Science Foundation Presidential Young Investigator Award Program.

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