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THESIS ABSTRACT

THE OHIO STATE UNIVERSITY
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DEPARTMENT: Atmospheric Science DEGREE: Master Of Science

ADVISOR'S NAME: Hobgood, Jay, S.

TITLE OF THESIS:

METEOROLOGICAL FACTORS THAT AFFECT THE FORMATION AND PREDICTION OF AIRCRAFT ICING

This thesis reviewed factors which influence aircraft icing, verified previous NACA data, and assessed forecasting techniques. Analysis of RAOBs and PIREPs compiled by NOAA/FSL were required to have occured within one hour of RAOB ascent and within 50 miles of the RAOB location. The results of this study compared favorably to those of NACA. Icing reports appeared to occur within a distint range from 0°C to -20°C and with a 1°C dew point depression. While not as distinct, stability is related to the type of icing. Current forecast rules were found to be valid and suggestions for improvement are provided.

Jay S. Hobgood
ADVISER'S SIGNATURE

METEOROLOGICAL FACTORS THAT AFFECT THE FORMATION AND PREDICTION OF AIRCRAFT ICING

A Thesis

Presented in Partial Fulfillment of the Requirements for the
Degree of Master of Science to the
Graduate School of The Ohio State University

by

CHRISTOPHER SEAN BJORKMAN, BS

xxxxxxxxxxxxxx

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1994

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CHAPTER I

INTRODUCTION TO THE PROBLEM

The renewal of interest in icing may be surprising, but it should have been expected. Experience with safety and operational issues has been that the problems are solved for a time, and then, as aircraft designs and operating practices change, the same problems often reemerge. Solutions require a renewed effort, often at a finer-scale than was previously necessary. Icing hazards to aircraft were thoroughly researched nearly two and a half decades ago. The last reports to summarize what was known on icing meteorology, forecasting, ice accretion, and on ways to prevent ice formation or remove ice from surfaces critical to flight, were written at the midpoint of this century (Enders 1979).

Within a decade of the completion of these earlier studies of aircraft icing, the air carrier fleet moved from propellor driven aircraft to jets. The operation of the jet was characterized by rapid climbs with plenty of power to altitudes above most weather, including icing. Low terminal traffic densities of that day allowed a swift descent to landing with little time at icing levels. General aviation and some military traffic continued to contend with icing problems. However, the greater knowledge of the effects of icing resulted in safer operation of aircraft. As a result, icing, as a subject of applied aviation research, disappeared except in studies relating to occasional icing-related accidents. Within the past few years, several things have happened to bring renewed interest to icing. New aerodynamic designs have emerged which raise questions of icing vulnerability for which the existing data are believed to be inadequate. One question is whether the previous work can be extrapolated to today's aircraft where operational reliability and dependability expectations are high. Expanded flight regimes for rotorcraft and general aviation aircraft have increased their exposure to icing.

The earlier attempts to forecast aircraft icing began with the accumulation of climatological icing data during World War II. These were followed by reconnaissance research flights by the Air Force and statistical analyses by the National Advisory Committee for Aeronautics (NACA) in the early to late 1950's. The work cumulated with the production of the United States Air Force (USAF) Air Weather Service Technical Report (AWS TR) 'Forecaster's Guide on Aircraft Icing', when it was believed that aircraft icing had been mostly eliminated as a problem on the then current airframes. However, the conclusion was not justified by later experience. Aircraft ice accretion continued to be important and it was either the cause or a contributing factor in 803 aviation accidents in the continental United States between 1975 and 1988 (Cole and Sand 1991). Although the majority of accidents involved general aviation or commuter aircraft (Telford, 1991), airframe ice is a problem for commercial operations as well. In spite of the earlier research, weather factors responsible for creating hazardous icing conditions are poorly understood (Sand, Politovich, and Rasmussen, 1990).

In 1978, NASA initiated a new research program on aircraft icing. Because of the elapsed time since the earlier studies, the work was conducted by research and engineering personnel with no previous experience in icing. NASA began by funding studies to determine the needs of the three major aircraft classes: large transports, commuters and general aviation, and helicopters. During the developement of the infrastructure for the study of icing, it was discovered the technological aspects of aircraft icing were virtually unknown in academia. Researchers at universities were funded to develop the technologies identified by the industrial studies. The research was conducted in concert with industry to ensure that the right problems were addressed and to facilitate technology transfer to industry. Then, the Federal Aviation Administration (FAA) began sponsoring a program, the Icing Forecasting Improvement Program (Hinkelman, 1989). Until this program, there were numerous projects and workshops on aircraft icing, but most of the work had been at the aerodynamic end of the problem. This trend created a need for better forecasts of aircraft icing and pilots with the necesary training to recognize icing on the more advanced aircraft. Currently, the FAA is in the fourth year of the six-year program to improve aircraft icing forecasts (Sand, Politovich, and Rasmussen, 1990). While progress has been made, numerous defiencies have been found, including an inadequate data base of meteorological parameters of the icing environment (Schultz and Politovich, 1992). However, these data are the only ones avaliable and are being used in current modelling attempts (i.e. Curry and Liu, 1992).

The purposes of this thesis were (1) to review the meteorological factors influencing the aircraft icing environment, (2) to review the problems faced by forecasters in prediction of these conditions, (3) to verify the extrapolation of the older data, and (4) to assess current forecasting techniques. These goals were met by an analysis of upper air soundings (RAOBs) and Pilot Reports (PIREPs) data which were compiled for the FAA's icing program at the National Center for Atmospheric Research (NCAR). To ensure the accuracy of the atmospheric parameters associated with the icing reports (i.e. Forbes, et al., 1993), the PIREPs were required to have occured within one hour of RAOB ascent (from 1100 to 1300 UCT for the 1200 UCT sounding and from 2300 to 0100 UTC for the 0000 UTC sounding) and within 50 miles of the RAOB location.

Research papers associated with icing often discuss the basics of aircraft icing by referring the reader to the Air Force document, "Forecaster's Guide on Aircraft Icing", which despite a 1980 update, has 48 of its 56 references dated before 1960 (Modica and Heckman, 1993). Despite the age of much of the work on which the report was based, it remains as the most comprehensive paper on the subject and the best reference available for the operational forecaster. A review and update of this document is long overdue. Much of the current research on the prediction of icing has attempted to model icing events or discuss the aerodynamic factors verses the meteorology. Therefore relatively little attempt has been made to compare the empirical data to that gathered during the research of the 1950's or to attempt a meteorological index derived by RAOB data alone that may provide insight to icing forecasts (Sand, Politovich, and Rasmussen, 1990). Another goal of this thesis was to produce an update of the 'forecaster's guide' that incorporates this thesis data, to confirm if an icing index derived from RAOB data alone is posssible, and to produce an updated checklist for forecasting aircraft icing.

CHAPTER II

HISTORY OF RESEARCH ON ICING

Once aircraft became capable of extended flight the problems and hazards associated with ice on the airframe became apparent. At times icing has been the subject of intense investigation. As long ago as 1930 (Scott, 1930), wind tunnel experiments on the icing problems were made, and by 1938 research papers and guidance to forecasters had been published in many countries (Biggs 1937, McNeal 1937, Findeisen 1938). In the early days, aircraft subjected to heavy ice accretion were frequently forced to land because of the lack of reserve engine power. With the advent of more powerful aircraft, greater reserve power in the engines, de-icing or anti-icing facilities and with the virtual elimination of engine icing on piston engined aircraft, the hazards were greatly reduced. The reserve power and de-icing facilities were usually sufficient to allow the aircraft to fly outside the region where the icing occured. Nevertheless, there were still some occasions when the safety of the aircraft was jeopardized by a rapid and severe ice accretion. It was thought the icing problems would be considerably reduced for turboprop and jet aircraft . This has not been the case. Engine icing problems may be more dangerous on modern aircraft even though airframe icing may be less severe. Penalties on performance introduced by even small amounts of airframe icing are considerable on aircraft where clean aerodynamic lines are essential for economic operation. The increased density of traffic, particularly around aerodromes, has curtailed the freedom of the pilot to leave the region of icing conditions by either horizontal or vertical deviations of the flight plan. With the trend of increasing numbers of light aircraft and the development of vertical take-off aircraft, both which are particularly susceptible to icing, it becomes clear that the risk of icing cannot be dismissed by the forecaster. Thus, this re-examination of the meteorological conditions associated with aircraft icing is quite timely.

The 21st Weather Squadron in London during World War II was the first to address aircraft icing in 1946 with the publication of "Aircraft Icing over Northwest Europe." Thirteen hundered flights were made from 3 June 1944 to 3 May 1945 . The elements observed included measured low and middle cloud altitudes, estimated altitudes of high clouds, visibilities aloft to the ground, precipitation, icing, turbulence, and condensation trails. Specifically relevant to this paper, was the examination of the relationship between actual cloud structure and the elements of radiosonde ascent.

In the early 1950's, NACA (National Advisory Committee for Aeronautics) did extensive research into airframe icing with wind tunnels. A summation of this research is presented by Jones (1956, 1961). The research cumulated in the publication of Air Weather Service (AWS) Technical Report (TR) 80/001 (originally AWS Manual 105 in 1969 and reissued in 1980). This document was written as a comprehensive guide for operational forecasters and discusses the physics and distributions of free atmosphere ice, the operational impacts of ice on aircraft, the synoptic setting for icing and a suggested outline for forecasting aircraft icing. This document, though still the most comprehensive, is outdated as it is based on the research of the early 1950s and has only a few modern references to radar (Modica and Heckman, 1993). Most importantly, NACA noted that the data may be skewed as the research aircraft flew patterns in conditions extremely condusive to aircraft icing.

In 1969, the USAF's AWS updated the climatology from their 1946 study in "Aircraft Icing Climatology for the Northern Hemisphere". The project used the empirical icing data gathered by USAF AWS reconnaissance flights along with soundings from 380 radiosonde stations in the Northern Hemisphere. The final report produced at the end of the project included an update of the methodology used within AWS to determine the climatological probability of aircraft icing throughout the Northern Hemisphere. The report contained isopleth charts of the 1000 mb, 850 mb, 700 mb and 500 mb surfaces for each of the twelve months. A station listing and locator chart provided areal coverage of the data used in the computerized calculations. The Air Force updated the climatology of icing with these data and through the use of computer models for North America (AWS 1986).

Due to escalating costs for aircraft and concerns about safety, the interest in icing research has re-developed. This work re-examined the technical issues involved in aircraft icing, which included the data base, analysis methods, test techniques, and test facilities (Beheim 1979). This began in 1979 with a conference sponsored by NASA which was convened to identify areas of concern (Enders 1979). In 1981, the National Transportation Safety Board (NTSB) published a comprehensive safety report on aircraft icing. This report presented icing statistics, the meteorological factors which cause icing, the consideration of icing during the certification of aircraft by the FAA, and the forecasting of icing conditions. Evidence of the continued hazard posed by icing was that during the 1976 through 1979 period there were 178 aircraft accidents involving structural icing (based upon National Transportation Safety Board records as of January 1, 1981), which was about one percent of the 16,997 total accidents that were recorded during the period. Of the 16,997 accidents, 2,869 (17 percent) were fatal. In the 178 icing accidents, 100 (56 percent) were fatal. While icing is an infrequent factor in aircraft accidents, it is a hazardous one. An increase in the number of instrument flight rules (IFR) operations has been apparent in recent years. From 1973 through 1977, the number of instrument ratings issued to pilots increased by 96 percent. During this same period actual IFR operations increased by 104 percent. As this trend continues, spurred on by improvements in engine reliability, radios, navigational aids, and autopilots, an increase in aviation icing encounters is likely as pilots fly more often in icing eenviroments. Of aircraft registered in the US, only about 12,000 (6 percent) are certificated by the FAA for flight into known icing conditions, and even these are seldom equipped to handle severe icing. Consequently, the principal means of preventing accidents due to icing must be the avoidance of icing conditions. More recently, Cole and Sand (1991) presented an updated summary of the NTSB's aircraft icing accident data through 1988, and Telford (1991) describes an interesting case study of an icing related crash of a research aircraft which belonged to The Desert Research Institute.

The renewed interest in icing led the Air Force (Ladwig, 1986), private industry (Patnoe and Tank, 1993), and the FAA (Czekalski 1985; Sand, Politovich, and Rasmussen, 1990) to review their icing programs. Increased funding and research has included efforts to improve the icing data base (Jeck, 1983; Curry and Liu, 1992; Schultz and Politovich, 1992), and to conduct case studies (Sand, 1985; Hoffman et al., 1987; Bernhardt, 1989b; Peters, 1990), such as the National Center for Atmospheric Research's (NCAR) WInter Storms Project (WISP) (Rasmussen, Politovich, et al., 1992; Rasmussen and Baker, 1993). Additionally, the accuracy of current icing forecast techniques have been studied (Bernhardt, 1989a; Wilson, 1990; Miller, and Cairns, 1993) and an attempt has been made to improve the icing forecast through the use of numerical models (AWS 1984, Schultz and Politovich, 1992; Forbes, et al., 1993; Modica and Heckman, 1993; Schultz, 1993; Smart, et al., 1993). The improved data base should led to an improved understanding of the meteorological and aerodynamic parameters affecting aircraft icing, the basis of this thesis. There has been increased activity in numerous fields including de-ice/anti-ice devices, revised characterization of icing conditions, ice phobics, computer simulation, and flight tests. The Federal Coordinator for Meteorology is involved in two efforts, a national plan to improve aircraft icing forecasts and an associated warning service (Pass, 1988). The intent of these efforts is to improve the capabilities of government agencies to fulfill their various missions with regard to the effect of aircraft icing and to enable the U.S. manufacturers of aircraft to build safe, economically competitive aircraft.

Forecast efforts have included the study by Hansman (1982) and Popa Fitino et al. (1986) on the potential role of ground based remote sensors in the detection of conditions conducive to aircraft icing. Osborne (1989) studied the role of Doppler radar in identifying aircraft icing. It was concluded that under some conditions the measurements of liquid water are very useful in the detection of icing conditions. This variable is not generally available from radiosondes (Ladwig, 1986) except from research sensors like the microwave radiometer (Popa Fitino et al., 1986).

Cole and Sand (1991) looked at accidents directly caused by aircraft icing as well as those with aircraft icing as an attributable factor. Orographic, meteorological, and pilot factors that could have had a systematic effect on the icing accidents were studied from the NTSB accident reports. The study demonstrated the relationship of orographic features and large bodies of water to the frequency of accidents. Observed icing accidents were equally distributed among take off, in flight, and landing. Few general aviation aircraft are equipped for flight into known icing conditions. Sand and Politovich (1991) discussed the Federal Aviation Administration's six-year program to improve aircraft forecasts, which was initiated in October 1989. An overview of the national program to improve aircraft icing forecasts was presented by Hinkelman (1989). As part of the program, two months of field studies were conducted in the Denver area during the winter of 1990. The paper provided a status report on that effort, gave a summary of the observations, and presented a plan for an expanded study in 1991.

CHAPTER III

FACTORS AFFECTING AIRCRAFT ICING

The magnitude of the hazard to a particular aircraft in a potential icing situation is not one which the forecaster can be expected to know (Jones 1961). The duty of the forecaster is to forecast accurately in time and space the **meteorological** conditions which are believed to be of importance in causing icing on aircraft. It is the responsibility of the pilot to know the potentially adverse effects of aircraft icing. The effects of icing are complex and depend on meteorological and aerodynamic factors. In order to determine the importance of the meteorological factors, it is necessary to discuss some of the general aerodynamics factors.

The fact that water droplets exist in the supercooled state in the atmosphere was known many years before the first aircraft flight. A common experience at mountain observatories (Omond 1886) was to notice the formation of both clear and rime ice when the observatory was in a cloud at temperatures below 0°C. The maximum rate of growth of Rime ice was approximately half an inch per hour in those conditions. Aircraft flying in similar conditions experience icing when flying in a cloud. Thus, the role of supercooled water drops in the developement of ice on aircraft is generally accepted. However, the interaction of supercooled drops with an airframe is a complicated process involving both meteorological and aerodynamic factors (Hardy 1946, Brun 1957).

Some of the meteorological factors involved with aircraft icing are (Jones 1961):

(I) supercooled water content of the air;

(II) ice crystal content of the air;

(III) temperature and humidity;

(IV) droplet and crystal size distributions;

The aerodynamic factors associated with airframe icing include:

(I) speed of the aircraft;

(II) temperature of the aircraft surface;

(III) efficiency of catch of droplets or crystals by forward facing surfaces, which itself depends on the curvature of the surface, the speed of the aircraft and the size of the droplets or crystals.

Aircraft icing presents a serious weather hazard for flight. When flying at subsonic speeds in visible moisture at temperatures near or below freezing (i.e. supercooled clouds), the pilot must expect an encounter with icing. In the absence of thermal protection or fluid ice protection, supercooled droplets striking aircraft components will freeze onto them. The droplets freeze by releasing their heat of fusion to the air flowing over the component. Structural icing is the accretion of ice on any exposed surface of an aircraft due to the impact of supercooled water drops on that surface (NTSB 1981). Normally, there are only two meteorological elements involved in structural icing: liquid moisture and subfreezing temperatures (Lewis 1951). In addition, frost may occur as water vapor sublimates directly onto surfaces as crystals.

Icing creates many potential hazards for pilots. The buildup of ice distorts the shape of airfoil surfaces reducing lift and increasing stall speeds. The additional weight decreases performance and increases fuel consumption. Rotating airfoils such as propellers and helicopter rotors also suffer the distortion of shape and the increase in weight due to the accretion of ice. Ice can block air intakes and cause engines to overheat and lose power. In the case of turbine engines, ice that has broken loose from other parts of the aircraft can cause damage to compressor and turbine assemblies. Ice can cause operational problems such as loss of visibility due to ice on windscreens, attenuation of radio and radar signals from ice on the radomes and antennas, and erroneous readings on pressure instruments such as the altimeter and airspeed indicator due to accretion on the pilot static ports.

Structural icing can be divided into three types: Rime, Clear, and Frost (AWS 1946, 1980; Jones 1961; NTSB 1981). Frost is a hazard since any ice on an airfoil will reduce the performance of the airfoil. When the maximum performance of the aircraft is required even a small performance loss may be unacceptable. Frost often forms on the cold surfaces of an aircraft when descending into humid regimes, but this usually evaporates at lower altitudes and seldom causes serious difficulty.

Rime ice is a rough, milky, opaque formation of ice caused by the impact of small supercooled droplets as seen in Figure 1. The droplets retain much of their spherical shape upon impact, trapping air between them and creating the milky appearance. Because Rime particles retain their shape, they build up at the point of impact and develop shapes which distort the airfoil. The shape formed depends on the airflow and the length of time the ice accumulates. If the accumulation is heavy, the original distortion changes the impact points and further distorts the airfoil. Because the droplets freeze on contact, Rime ice has little tendency to spread, and can be eliminated by de-icing or anti-icing surfaces. Additionally, its porous quality makes it brittle, which allows it to be broken off by de-icing equipment such as the inflatable boot.

Clear ice is a glossy, clear to translucent accumulation formed by large droplets or raindrops which spread and freeze on contact forming a sheet of smooth ice. It is the most hazardous of icing conditions because it accumulates rapidly and it can become dense and heavy. Clear ice often spreads beyond the effective area of de-icing or anti-icing surfaces and adheres strongly to the aircraft's surfaces (Sand, 1985; Politovich, 1993) and is shown in Figure 2. Rime and Clear icing are unique conditions, each with a particular set of circumstances for development. In nature, the circumstances causing each type of icing often co-exist, and actual icing is a combination of Rime and Clear ice, referred to as Mixed icing and is displayed in Figure 3. The characteristics of the mixture depend upon the weather conditions present. A common shape is the "ram's horn" in which the ice accumulates away from the leading edge of the airfoil, both above and below it, forming a shape similar to that of the horns on a ram. An illustratation is shown in Figure 4.

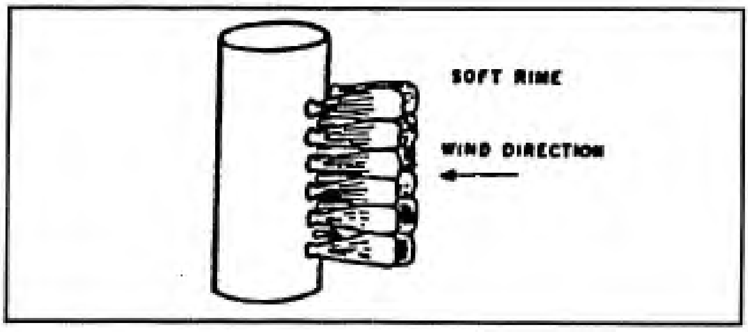


FIGURE 1, RIME TYPE ICE (Talbot, personal communication)

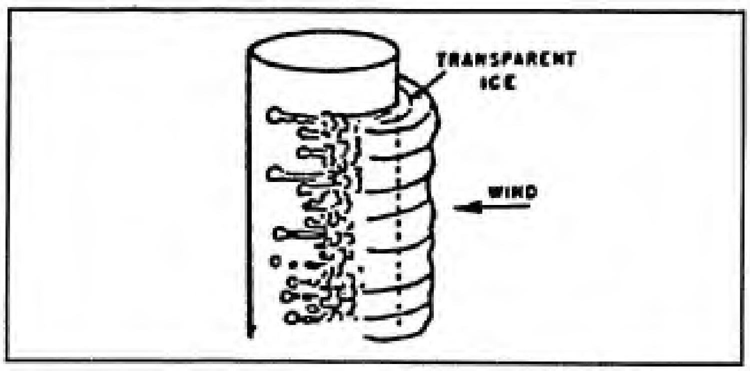


FIGURE 2, CLEAR TYPE ICE (Talbot, personal communication)

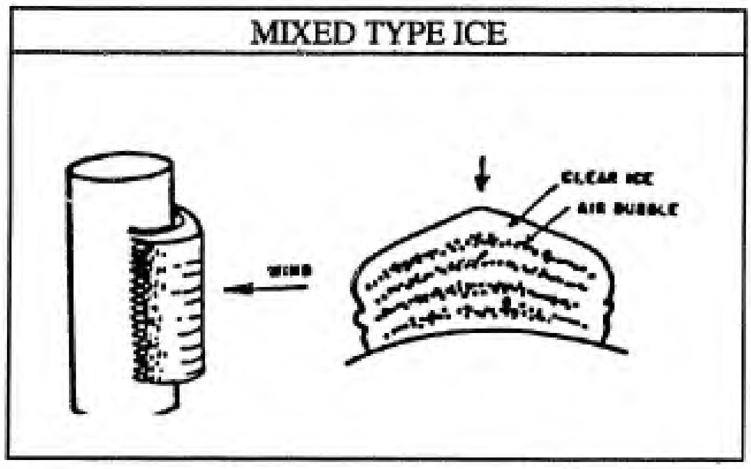


FIGURE 3, MIXED TYPE ICE (Talbot, personal communication)

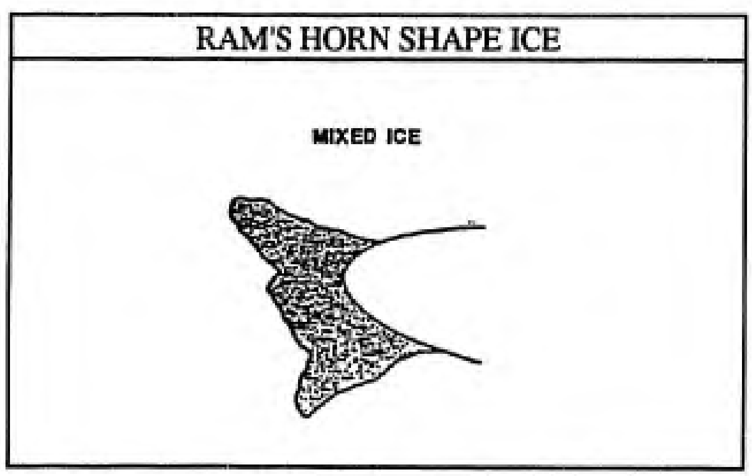


FIGURE 4, RAM'S HORN SHAPE ICE (from Hansman, 1987)

Icing forecasts generally cover a larger volume of the atmosphere than the actual icing conditions. Usually the numbers and kinds of observations are not sufficient to describe precisely the icing envelope, and the forecaster must use limited available data. The present definitions of icing intensity that are used in the forecasts were established in 1968 by the Subcommittee for Aviation Meteorological Services of the Federal Coordinator for Meteorological Services and Supporting Research (AWS 1980; NTSB 1981).

(1) **Trace of Icing**. Icing becomes perceptible. The rate of accumulation is slightly greater than the rate of sublimation. It is not hazardous even though de-icing/anti-icing equipment is not utilized, unless encountered for an extended period of time over one hour.

(2) **Light Icing**. The rate of accumulation may create a problem if flight is prolonged in this environment over one hour. Occasional use of de-icing/anti-icing equipment removes/prevents accumulation. It does not present a problem if the de-icing/anti-icing equipment is used.

(3) **Moderate Icing**. The rate of accumulation is such that even short encounters become potentially hazardous and use of de-icing/anti-icing equipment or diversion is necessary.

(4) **Severe Icing**. The rate of accumulation is such that de-icing/anti-icing equipment fails to reduce or control the hazard. Immediate diversion is necessary.

A problem with these definitions is that a liquid water content and drop size distribution may produce light icing on one aircraft and moderate icing on another (NTSB 1981). However, the forecaster is not able to differentiate between all of the types of aircraft that might be experience a given icing condition. A forecasting system is needed which will allow the pilot to determine the icing effects on a particular aircraft and to use this to prepare a safe flight plan. This would allow the most effective use of airspace as dictated by the weather and the aircraft.

An immediate problem which was associated with the definitions of icing severity appeared in a review of the federal regulations governing the operation of aircraft (NTSB 1981). In both FAA regulation's CFR 91 and 135, aircraft are restricted from flying into known or forecasted severe icing conditions unless the aircraft has met the conditions of Federal Air Regulation No. 23 and are allowed to fly in these conditions. Yet, by the definition in the Airman's Information Manual, severe icing describes a rate of accumulation that de-icing/anti-icing equipment cannot effectively overcome. There appears to be a dangerous contradiction here. An aircraft could legally fly into an area of severe icing under CFR 91 and 135, yet by another definition the aircraft is not certified to control the hazard. The conflicting regulations need to be reviewed to allow them to complement the definitions of icing severity. A summary of the National Transportation Safety Board icing statistics through 1988 with the FAA's icing regulations, FAR 91-52 and 53, can be found in Cole and Sand (1991).

Although all concerned US Federal agencies have now agreed to the standard definitions of icing intensities, international standardization has not yet been accomplished (AWS 1980). Some other countries use completely different terms to describe the intensities and types of icing and give no indications of the aircraft type to which their icing intensities refer. The World Meteorological Organization (WMO) uses ten code figures in the terminal aerodrome forecast (TAF) for icing but does not explain the meaning of the intensities and does not refer to any standard aircraft type.

While this paper deals with in-flight aircraft icing, certain icing hazards may also develop on or near the ground. Alleviation of these hazards is the responsibility of flightline personnel, but the existence of such conditions should be mentioned in a weather briefing. One hazard results when wet snow is falling during takeoff. This situation can exist when the air temperature at the ground is near 0°C. The wet snow sticks to aircraft components, particularly the wings, and freezes when the aircraft encounters colder temperatures during its climb. If they are not removed before takeoff, frost, sleet, frozen rain, and snow accumulated on parked aircraft represent operational hazards. It is common practice to place aircraft in a hanger until the accumulation has melted, or to clean the airfoil surfaces by some other means before a flight is attempted.

Another hazard, which is not widely discussed, comes from the presence of puddles of water, slush, or mud on airfields. When the air temperature and the airframe temperature are colder than 0°C, water blown by the propellers or splashed by wheels can form ice on control surfaces and windows. Freezing mud is dangerous because the dirt may clog controls and cloud the windshield. Mud, slush, or water which freezes in the wheel wells and on wing flap hinges may prevent the retraction of wheels or flaps or may cause them to freeze in a retracted or semi-retracted position.

METEOROLOGICAL FACTORS AFFECTING AIRCRAFT ICING

Knowledge of the physics which control aircraft ice accretion is necessary for accurate identification and prediction of icing conditions. The severity of aircraft icing is sensitive to temperature, liquid water content and droplet size distribution, particularly for the transition between Rime and Mixed icing. The operational difficulties in measurement of these factors and the variability of the variables with altitude, position and time make forecasting and identifying icing conditions difficult. Automated Pilot Reports (PIREPs) may provide one mechanism for improving the data base necessary to forecast icing conditions (Hansman 1989).

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

The ice accretion process is controlled by two distinct subprocesses (Hansman, 1989) of which the first is the transport of liquid water (either in the form of cloud droplets, rain drops or mixed phase hydrometeors) from the environment to the aircraft surface and the second is the freezing of the droplets. Once droplets have impacted the surface, their freezing becomes controlled by thermodynamic processes. If the heat transfer is sufficient to remove the latent heat of fusion of the water, then the droplets will freeze on impact resulting in a dry ice surface. The ice shape protrudes forward into the airstream and is referred to as Rime ice as depicted previously in Figure 1.

When the heat transfer from the surface is inadequate to remove all the latent heat from the droplets, then the surface becomes wet. This type of accretion is glaze or Clear ice and is depicted in Figure 2. In some cases, both wet and dry ice growth can occur at different places on the same body. This is referred to as Mixed ice growth as shown in Figure 3. Often in Clear or Mixed conditions, the resulting shape displays two pronounced growth peaks on either side of the stagnation line. The most severe aircraft performance degradation is associated with such horned ice formations (Renaudo, et al., 1984). Because the physics of Mixed and Clear icing are similar, the term Mixed icing will refer int his section to both Mixed and Clear type icing.

The physical processes which control ice accretion are different for dry and wet ice growth (Hansman et al.. 1987). In dry growth, where the droplets freeze on impact, the accretion is controlled by the rate of impact of liquid water on the surface. The flux of liquid water is an inertially determined quantity which is a function of the individual droplet trajectories as they pass through the flow surrounding the body. For wet growth, the accretion is controlled by the rate at which latent heat of fusion is removed from the surface. The heat transfer from the surface becomes the mechanism for wet ice growth. For mixed conditions, both the impact and heat transfer play important roles in the ice accretion process.

The physics which control the impact of liquid water onto the surface is fairly straight forward. Because the surface is not permeable to gas, flow streamlines do not intersect the body. Water droplets have a higher ratio of inertia to hydrodynamic forces than gas and will tend to cross the streamlines resulting in impact, see Figure 5 and Figure 6.

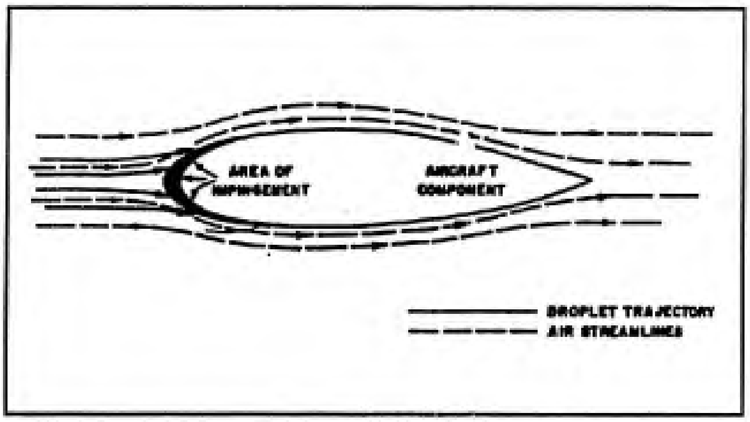


FIGURE 5, AREA OF IMPACT (after AWS, 1980)

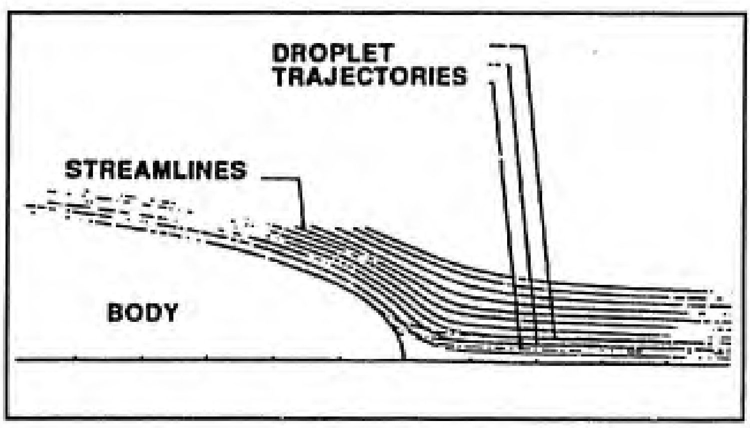


FIGURE 6, WATER DROPLET TRAJECTORIES (Bergrun, 1947)

Much work has been done on droplet impingement trajectories to determine local collection efficiencies (Bergrun, 1947, Bragg, et al., 1981, Brun et al, 1953, Gelder, et al, 1956, Hansman, 1981). The collection efficiency is defined as the ratio of the mass impinging onto the surface of the freestream mass. The efficiency is typically higher near the stagnation point and decreases downstream. The point at which the collection efficiency becomes zero is defined as the Impingement Limit and the collection efficiency of this point is a function of droplet size and body geometry. Large droplets have high inertia which causes them to cross streamlines resulting in high collection efficiencies and impingement limits (Politovich, 1989a) while 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.

The heat balance on the accretion surface is a factor in determining the rate of accretion in Mixed conditions and is the critical factor in determining the transition between these conditions and Rime ice growth. Figure 7 shows the principle modes of energy transfer associated with an icing surface as depicted by Messinger (1953).

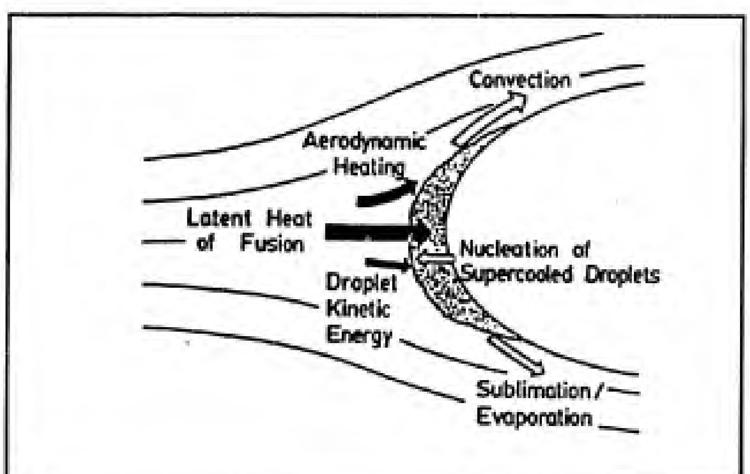


FIGURE 7, AIRCRAFT SURFACE HEAT TRANSFER (from Hansman, 1987)

Heat is added to the surface primarily from the latent heat of fusion released as the droplets freeze. Some of the energy is also added by aerodynamic heating and from the kinetic energy of the droplets. 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 droplets impinge and warm to 0°C. The parameters which 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.

Next, the influence of meteorological parameters which are considered important to aircraft icing are discussed in terms of their effect on the physics and the severity of the ice accretion. This has been reviewed extensively by R. John Hansman (1984, 1987, 1989), who related icing to typical cloud and precipitation distribution. The results were used to generate a distribution for typical cloud and precipitation size distributions. In addition, Hansman (1989) wrote an excellent summary of the physics which control aircraft ice accretion in the context of identifying hazardous icing conditions. Hoffman and Roth (1988) conducted research flights to investigate the cloud parameters associated with aircraft icing. These data were used to determine the dependence of the physical parameters on the type of cloud . Sand (1988) reported on the effects of orographic lifting on the potential for aircraft icing. It was found that airways which are along or over the crest of hills or mountains are potential locations for serious icing encounters. This effect was shown to be quantifiable and should be considered when analyzing and forecasting icing conditions.

Air temperature is one of the most important of the icing parameters (Politovich, 1993). 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 8 (Hansman, 1987) it can be seen that the differences between stagnation and ambient temperature (TAT-OAT) may be as high as 30°C at 500 kts.

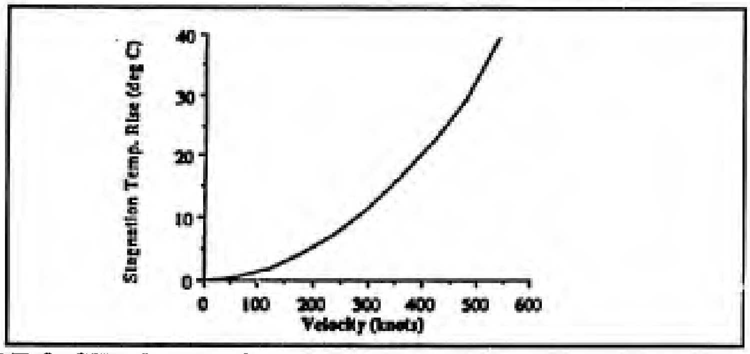


FIGURE 8, STAGNATION TEMPERATURE RISE (after Hansman 1987)

Because the surface temperature can be lower than the TAT behind 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 (Huffman and Norman, 1988).

An example of the effect of temperature on accretion and performance degradation was discussed by Olsen et al. (1984). At cold temperatures, the accretion rate was insensitive to temperature, and rime accretions were observed with drag increases of two to three times the clean values. However as the temperature increased above -10° C, the drag due to the icing increased sharply as the temperatures increased to a peak value of over eight times the clean drag. The cause of the increased drag was the transition from a dry Rime growth to a wet Mixed growth. The horns characteristic of Mixed growth can be observed in the high ice accretions (Sand, 1985). As the TAT nears 0°C the accretions and the 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 benign rime icing condition to a dangerous Mixed condition. The nonlinear dependance of icing severity on TAT, combined with aircraft velocity effects, makes it difficult to identify accurately regions of moderate or severe ice potential from the air temperature alone.

Liquid Water Content (LWC) influences the severity of the icing in two primary ways (Politovich, 1993). First, increasing LWC implies more potential water and larger accretions within a given time. Thus, high LWC implies a greater urgency and severity of the icing encounter. The second effect of high LWC is the transformation of Rime type ice to Mixed icing due to higher water load on the surface. 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. However at some value of LWC , the growth will change from Rime ice to Mixed ice and the severity of the icing will increase. At colder temperatures the threshold for the transition occurs at a higher liquid water content.

An additional factor which complicates the accretion process is the variability in LWC within the same cloud (Hoffman and Roth, 1988). In a study by Hansman and Kirby (1987) of a research flight, the stagnation point was monitored to determine whether the accretion was dry, wet or transitional. The variation in LWC caused the accretion to vary from dry growth of rime ice to wet ice growth of mixed ice within the same cloud. The size of the water droplets in terms of the Median Volumetric Diameter (MVD) and the shape of the Droplet Size Distribution can be important to the accretion process (Hoffman and Roth, 1988; Hauf, 1993; Politovich, 1993). As described, large droplets are more efficiently caught by a body. These effects have been quantified for typical cloud and rain size distributions by Hansman (1986). The bulk of the impinging mass resulted from the small number of large droplets in the tail of the distribution. The MVD and the shape of the distribution determine the effective collection efficiency of the aircraft. Trace or negligible icing even at high liquid water contents for clouds of small droplets is not uncommon. Moderate to severe icing at relatively low liquid water contents for distributions consisting of large droplets is also possible (Politovich, 1989a).

The presence of large droplets within the cloud distribution can result in additional hazards due to increased impingement limits. The limit of droplet impact on an aircraft component increases with droplet size. Current design guidance; the FAA AC-20-73 in 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 result in accretions occurring behind the protected regions of the aircraft. Politovich studied the role of large droplets on the icing process (1989a) and the measurements of environmental parameters by aircraft (1989b). These factors are thought to contribute to the high performance degradations observed by Cooper, Sand, Politovich and Neal (1984) and Politovich (1989a;1989b) 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 LWC are combined. Freezing rain results in Clear ice accretions with significant runback icing resultingin an extremely hazardous condition. The icing potential for a cloud is related to the phase of the hydrometeors. Icing normally results from the impact of supercooled water droplets. Dry ice crystals generally do not adhere to the surface after impact and are not considered an icing hazard. If, however, the ice crystals are wet due to partial melting or the aircraft is wet due to de-cing from a high LWC region, then the impinging crystals will stick. Mixed phase icing (not to be confused with Mixed Rime/Clear icing) is relatively rare.

Some examples of Mixed phase icing have been observed in flight tests by Gayet, Bain and Soulage (1984) who noted that the presence of snow in clouds significantly reduced the icing rate. Ice crystals sticking on wet surfaces was observed during NASA's Icing Research Aircraft flight tests at times when the wet surfaces existed (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 of the statiform cloud results only 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 themselves.

A factor which has emerged as possibly important to accretion is the fine scale (centimeter and below) turbulence level. The turbulence level is known to influence the convective heat transfer from the icing surface. The convective heat transfer is one of the parameters in determining transition between Rime and Mixed icing with effect on icing severity. Flight test observations by Hansman and Kirby (1987) observed variability in the threshold between rime and mixed icing. The variability was thought to be due to variations in heat transfer from the turbulence level. While the effect of fine scale turbulence on severity has not been directly demonstrated, it may be a source of uncertainty in the forecasting process.

AERODYNAMIC ASPECTS OF AIRCRAFT ICING

An important chapter in the historical evolution of aircraft is that related to icing research (Beheim 1979). From 1940 to 1955, the efforts made in industry and at government laboratories (particularly NACA) were directed toward defining the natural icing environment, determining its effects on aircraft components, and designing techniques for ice protection. The results established a basis for certification criteria and meteorological reporting procedures that proved to be generally acceptable to achieve all weather capability for the large transport aircraft of that time. When this effort ended in the late 1950's, the emphasis in the design of transport aircraft had shifted to jet power. Because of higher power and high cruise altitudes, these jet aircraft were exposed less to ice (Sand, 1988). In fact, they were even more ice tolerant than propeller transports. The manufacturers of these aircraft continued to develop increasingly sophisticated analysis and testing techniques for icing protection that were tailored to the aircraft being certified. Although the certification criteria were recognized to be conservative, the penalties to aircraft performance and cost were not excessive since large quantities of heated, high-pressure air were available from their power plants for ice protection systems on the engines and airframe. For many components of aircraft it even became possible to eliminate the ice protection systems entirely because their physical size was so large that accretion was minor and the resulting aerodynamic influence was acceptably low. This trend in the design of new large transport aircraft continues today. However, in a period of escalating development costs for aircraft, there is growing interest in a renewed and coordinated icing research effort to achieve an updating or modernization of the issues that are involved including the data base, analysis methods, test techniques, and test facilities.

In recent years it has become necessary to extend the technology to new classes of aircraft: rotorcraft and general aviation (Beheim 1979). The emerging small aircraft may operate more frequently in icing environments than large jet transport. The advances achieved in avionics provide the opportunity to operate in adverse weather with smaller aircraft as well as with the large transports. However, the icing protection requirements for small aircraft are different from large transports so that an extrapolation of the current base of icing technology may be inadequate. The components of these aircraft are smaller so proportionately heavier accretions of ice are likely to occur. Consequently, their aerodynamic performance will deteriorate more drastically. Penalties for the weight of icing protection systems are more severe since the payload fraction is already relatively low. In addition, their engines differ so large quantities of high-pressure, heated air are not available for ice protection. Consequently, the important issues not only include those listed earlier for transport aircraft but extend to nonconventional ice protection concepts. Furthermore, the certification criteria and weather reporting procedures for large transport aircraft need to be reexamined for their applicability to small aircraft.

The influence of various aircraft parameters which are considered important to the icing problem are discussed in terms of their effect on the physics and severity of the ice accretion (Hansman 1989). The aircraft velocity affects both the collection of liquid water and the thermodynamics of the icing process. Increasing velocity results in higher impinging liquid water exposure by increasing the path swept out by the aircraft and the collection efficiency of the aircraft. Thermodynamically, the velocity affects the heat load through the increased water mass and through increasing the stagnation point temperature at high velocities (Lewis, 1951; Jeck, 1983; Politovich, 1993). This was shown in Figure 8 (Hansman 1987) where the stagnation temperature rise was plotted as a function of velocity.

The shape of the body has an 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 accretion. As a result of their high collection efficiencies, windshield wipers or Outside Air Temperature probes are often used by crews to detect icing in flight. Three dimensional shape effects can be important for many components. For example, wing sweep results in spanwise variation of the accretion in mixed conditions. This "lobster tail" ice can result in significant performance degradation. Worth noting is the fact that current forecasting procedures are based on straight wing propeller driven aircraft (USAF, 1980).

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. 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. 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 aircraft the wings. Therefore, critical regions are normally anti-iced with hot bleed air from the engines to prevent any ice accumulation.

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 in icing conditions at night. 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 the propellers because loss of propeller efficiency translates into loss of thrust. However, even airframe icing can pose a significant hazard because propeller driven aircraft 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.

Helicopter icing has become important during the last decade where helicopter flight in Instrument Meteorological Conditions (IMC) has become commonplace. Operations occur almost exclusively at low altitudes where there is significant icing potential. Helicopters are extremely susceptible to icing conditions (Czekalski, 1985). Rotor icing degrades the lift and thrust efficiency of the vehicle. In addition, helicopters operate with very slim power margins and can only tolerate minimal ice accretion. Other hazardous factors resulting include; blockage of engine inlets, reduced control authority, vibration due to asymmetrical ice load on rotors and reduced visibility due to canopy icing.

There is a greater range of aircraft models and characteristics in airline inventories today than ever before. This range may become greater in the future, because new aircraft are being developed faster than the old ones are becoming obsolete. Therefore discussion in this thesis will be limited to the operational aspects of icing for general types of aircraft, rather than specific models. Overall, icing is a factor in a fraction of aircraft accidents and incidents. The proportion of all accidents due to icing has decreased considerably over the last 40 years, through better design and operating practices and the greater use of jets.

Aircraft engine icing is generally considered in two categories: induction icing or intake icing (NTSB 1981). Induction icing refers to the ice that is developed by the condensation of moisture inside of a carburetor due to the cooling effect of the venturi and the evaporation of fuel. This type of icing occurs most commonly in clear air and is not associated with liquid moisture in the atmosphere. Hence, it will not be discussed in this thesis. Intake icing is a type of structural icing where the air intake to an engine is partially blocked or distorted by ice. Intake icing differs from airfoil icing in that, rather than affecting the aerodynamics of the aircraft, it reduces the available power. The icing criteria for aircraft certification are based upon research done by the National Aeronautics and Space Administration in the late 1950's with the transport aircraft of that period. Although the results of this research and the practices and regulations that came out of it are still basically valid, there have been changes in aircraft, de-icing/anti-icing equipment, and improvements in the instruments used to measure atmospheric icing parameters.

Jet engines experience icing both externally and internally. All surfaces which are subject to direct contact with water droplets may collect ice, and the inlet ducting and internal elements are subject to icing. Similar to the carburetor icing of conventional engines aircraft, icing can occur on the inlet duct of a jet at temperatures above freezing, when the aircraft is operating on the ground or at low speeds. The greatest icing hazard, and the most difficult to protect against, involves the compressor inlet screen. The thrust produced by the jet engine is a function of airflow through the engine. Icing on the engine components reduces airflow, thus creating pressure losses, reduced thrust, and increased fuel consumption.

In the past, most military aircraft were equipped with de-icing equipment. Many of the newer models, particularly jet aircraft which operate at levels where icing is rare, are not so equipped. Although various waxes, paints, lacquers, and lubricants have been tried for de-icing or anti-icing purposes, there are still only three methods commonly used for preventing or eliminating airframe icing on aircraft. These three methods are mechanical boots, de-icing fluids, and heat.

When mechanical boots are installed, the leading edges of wings and tail surfaces are equipped with rubber skins which normally assume the contour of the airfoil. During icing situations, compressed air is cycled through ducts, causing a deformation of the boots. The stress produced by the boots causes the ice to fracture, and the air stream peels the ice from the boots. Mechanical techniques are used only after ice has begun to form. Anti-icing fluids are used on rotating surfaces where the centrifugal force produced by the rotation spreads the fluid over the surface. The fluids are effective because they prevent ice from adhering to the surface then centrifugal force can throw it off. Anti-icing fluids are most effective when applied before the icing begins. The application of heat to an icing surface to raise its temperature above freezing is the most obvious method. This is the system used most often on aircraft equipped with de-icing equipment. The leading edges of the wing and tail surfaces are heated by hot air or electrical means. On conventional aircraft, hot air from a manifold can be piped to those areas of the most serious icing. On jet aircraft, hot air can be piped from the compressor. Either type of heating may be continuous or cyclic. In the past, weight, heat exchange, and temperature effects on structure and electrical insulation limited a continuously heated (hot wing) system, and resulted in preference for the cyclic system. This is the most economical system with respect to weight. Although cyclic heating and continuous heating may be used to remove ice already formed, continuous heating is used for ice prevention (Hauf, 1993).

As noted, both de-icing or anti-icing systems are employed on aircraft (Czekalski, 1985). Modern systems include conventional pneumatic boots, pneumatic impulse deicers, several versions of electo-mechanical impulse de-icers, electrothermal de-icers, and freezing point depressant fluids. Anti-icing systems include hot air thermal anti-icing, electrothermal anti-icing, and freezing point depressant fluids.

Current research centers on mechanical impulse systems, because they do not depend on bleed air and are energy efficient. The impulse is generated by a high pressure pneumatic pulse or by an electo-mechanical pulse. The de-icer designated "electromagnetic impulse de-icer" consists of flat coils that fit inside the wing and do not alter the external characteristics of the wing. The other electo-mechanical impulse systems consist of wires embedded in a material applied over the outside of the wing. Although these impulse de-icers are energy efficient, they have the drawback of all de-icers, ice builds before de-icer actuation, and some ice remains after action. Since impulse de-icers are more effective than conventional boots, they may find increased application on aircraft where pneumatic boots would be the first choice. They may even replace thermal heaters on propellers.

Electrothermal de-icers are widely used on aircraft, and a challenging application is for helicopter rotor blades. The most common blade deicers consist of strips of electrical heaters. There may be as many as eight strips on the leading edge, with each strip being independently powered and controlled. Since electrical power on helicopters is limited, only one strip on each blade is operated at any time. Each strip melts the ice above the strip, and aerodynamic forces shed the ice. The heater strips are turned on and off in a sequence set to prevent melted water from running back and refreezing. The sequences and power levels depend on outside air temperature and liquid water content.

Thermal anti-icing systems are well developed, but are undergoing development to reduce weight and hot air requirements. Engines planned for future transports achieve high efficiency by increasing by-pass ratio and decreasing size. These engines will not supply sufficient air for thermal anti-icing. Hot air thermal anti-icing is attractive because it keeps the airfoil free of ice buildup, airframers will explore alternate methods of supplying hot air, such as auxiliary power units, electrical compressors, or possibly burners or "electric hair dryers" air heaters. However, in case the studies rule out alternative sources, the airframers are urging development of systems that do not depend on hot air. While all of the de-icing or anti-icing sytems remove most ice from the aircraft, accurate prediction of potential icing situations is still important for planes with limited or no de-icing capabilities.

SYNOPTIC DISTRIBUTION OF ICING IN THE ATMOSPHERE

The distribution of potential icing zones is a function of temperature and cloud structure. These factors vary with altitude, synoptic situation, orography, location, and season (AWS 1980). Structural icing is limited to the layer of the atmosphere lying between the freezing level and and no colder than the -40°C isotherm, although icing has occasionally been reported at temperatures colder than -40°C in the upper parts of cumulonimbus and other clouds. In general, the frequency of icing decreases rapidly with decreasing temperature, becoming rare at temperatures below -20°C. The vertical temperature distribution in the atmosphere is such that icing is usually restricted to the lower 30,000 feet (10,000 meters) of the troposphere.

The type of icing is dependent on temperature. Clear ice occurs at temperatures just below freezing, where as Rime ice is dominant at lower temperatures. According to older AWS reports , the relative frequency of icing by types was found to be as follows: Clear, 10%; Clear-Rime mixture, 17%; Rime, 72%; and Frost (in flight), 1%. Aircraft icing can occur in stratiform or cumuliform clouds. Icing in middle and low-level stratiform clouds is confined on average to a layer between 3,000 and 4,000 feet thick (1000 and 1300 meters, respectively). The intensity of the icing ranges from a trace to light, with maximum values occurring in the upper parts of the cloud. Both Rime and Mixed icing are observed in stratiform clouds. The main hazard lies in the horizontal extent of these cloud decks. High-level stratiform clouds are composed mostly of ice crystals and give little icing.

The area of most probable icing in cumuliform clouds is smaller horizontally but greater vertically than in stratiform clouds. Icing is more variable in cumuliform clouds because factors conducive to icing depend on the stage of development of the cloud. Icing intensities range from a trace in small cumulus to light or moderate in cumulus congestus and cumulonimbus. The most severe icing occurs in cumulus congestus clouds just prior to their change to cumulonimbus since, at this stage, glaciation has begun. Although icing occurs at all heights above the freezing level in a building cumulus, it is the most intense in the upper half of the cloud. Icing is restricted to updraft regions in a mature cumulonimbus, and to a shallow layer near the freezing level in a dissipating thunderstorm. Icing in cumuliform clouds is usually Clear or Mixed. Aircraft icing rarely occurs in cirrus clouds which contain a small proportion of water droplets. However, icing of light intensity has been reported in the cirrus anvil tops of cumulonimbus where updrafts contain considerable water at low temperatures.

In frontal systems, it is difficult to represent icing conditions by an idealized model, since the structure of clouds in frontal regions and in regions of low-pressure systems is complex. In general, frontal clouds have a higher icing probability than other clouds. It was estimated from NACA's research flights that 85 percent of observed icing occurs in the vicinity of frontal zones. The greatest horizontal extent of icing is associated with warm fronts, and the most intense icing with cold fronts.

Warm frontal icing may occur above and below the front. Moderate or severe Clear icing occurs where freezing rain or drizzle falls through the cold air beneath the front. This condition is often found when the temperature above the frontal inversion is warmer than 0°C and the temperature below the inversion is colder than 0°C. Icing above the warm front, in regions where the cloud temperatures are colder than 0°C, is confined to a layer less than 3,000 feet (1000 meters) thick. Jones (1961) found a possibility of moderate icing, usually Mixed or Clear, within 100 to 200 miles (150 to 300 km) ahead of the surface warm front. This was noticeable for fast moving, active, warm fronts. Light Rime ice was present in the altostratus up to 300 miles (500 kilometers) ahead of the surface warm front. Warm front icing is widespread while icing associated with cold fronts is spotty. Horizontal extent of cold fronts is less than the extent of warm front, and the areas of moderate icing are localized. Clear icing is more prevalent than Rime in the unstable clouds of cold fronts. Moderate Clear icing is limited to cumuliform clouds found within 100 miles of the surface cold front position, and is the most intense above the front. Light icing is often encountered in the layers of stratocumulus clouds behind cold fronts. Icing in the stratiform clouds of the anafront cloud shield is more like icing associated with warm fronts. Icing conditions associated with occluded and stationary fronts are similar to a warm or cold front. Moderate icing conditions are associated with deep cold low pressure areas where the frontal systems are diffuse. The characteristics of icing, which are dependent on cloud type and temperature, vary from one air mass to another. Icing is more prevalent in maritime than in continental air masses, and is more hazardous in regions of instability.

Statistics suggest that the radiosonde measured, analyzed, or forecast dew point spread at flight level can be used as an indicator of aircraft icing occurrence. The type of thermal advection or the presence of building cumuliform clouds, taken in conjunction with the dew point spread, showed an association with the occurrence and intensity of icing and these were obtained from NACA's research in the 1950's.

(1) When the dew point spread at flight level was 3°C or less in areas of warm air advection, there was a 67 percent probability of no icing, 20 percent and 13 percent probabilities of trace and light icing, respectively, and no probability of moderate icing. By contrast, when the dewpoint spread was 3°C or less at flight level in a cold frontal zone (frequently an area of intense cold air advection), the probability of icing approached 100 percent . There was nearly a 100 percent probability of icing in building cumuliform clouds when the dew point spread was 3°C or less.

(2) With a dew point spread greater than 3°C, trace icing was about 40 percent probable in regions of cold air advection while there was 100 percent probability of no icing in regions of neutral or warm air advection.

When compiling data, NACA personnel found considerable scatter in the relation of icing occurrence to dew point spread. They subjectively selected a 3°C spread as a convenient dividing line between large probabilities of icing or of no icing. NACA representatives stated that experience indicates that a 4°C dew point spread might be a more operationally realistic division point and that operational data should be analyzed for comparison.

In the theory of the formation of precipitation based upon the Bergeron-Findeisen theory, ice crystals were necessary in cold clouds to produce precipitation. Lewis (1951) concluded that steady precipitation at the surface should be an indication that icing in clouds over those areas would be light. During NACA flight tests to measure the properties of icing, a trace of ice was reported in 80 percent of the observations in clouds over steady precipitation areas and light icing was reported in only 20 percent of the observations. In stratiform clouds over areas without precipitation, the observed percentages were just the reverse. NACA found the presence of precipitation does not mean that icing will be trace. If the vertical motion caused by frontal slopes, terrain, or surface heating is sufficient to maintain a constant supply of supercooled water droplets, light or even moderate icing can be present in clouds over areas of steady precipitation.

High or steep terrain causes icing to be more intense than under identical conditions over low, flat terrain (Bernhardt 1989b; Cole and Sand, 1991; Rasmussen and Baker, 1993). Sand (1988) found, for example that a 500 feet (150 meters) increase in attitude at -10°C will produce an adiabatic increase in LWC of 0.14 gm/m^3 ,and that a 200 feet (70 meters) increase will generate 0.56 gm/m^3 of supercooled LWC, while the corresponding numbers at -20°C will produce 0.08 and 0.37 gm/m^3, respectfully. Icing is greater over the ridges than over valleys and greater on the windward side than on the leeward side. Moderate icing, usually Clear, is experienced in convective clouds over mountainous terrain. Windward, mountainous coasts in winter are subject to extensive icing zones. The lifting of maritime polar air by the mountains results in the formation of continuous supercooled clouds. Also, orographically induced updrafts permit air to support larger cloud droplets, so icing is more intense.

There is a variation between geographic areas in icing potential due to area to variations in temperature and moisture. For example, icing during the winter season is frequent over the warm water off the east coast of continents, to the lee of large inland water bodies, and over western portions of continents where winds transport ample moisture inland from the oceans. Because of the small amount of moisture in winter arctic air and the small liquid water content, icing is seldom regarded as a problem in the arctic in winter. It is not surprising that icing was reported by reconnaissance aircraft only 2 percent of the time over the Arctic Ocean at 10,000 feet (3300 meters). At the same altitude over the northern portion of the North Atlantic Ocean, icing was reported 19 percent of the time.

CHAPTER IV

STUDY OF ATMOSPHERIC PARAMETERS AS FACTORS IN AIRCRAFT ICING

The research in this paper had two main parts. The first and primary section was the analysis of the remotely sensed atmospheric parameters associated with confirmed aircraft icing reports. The aircraft icing environment as defined by remotely sensed data (RAOBs) and verified by PIREPs (a direct report of icing conditions which includes altitude, geographic location, the type of aircraft and the type and intensity of the icing) was seen as being instrumental in aiding operational weather forecasters. These results may help to explain the conditions conducive to aircraft icing and hopefully may aid researchers, primarily those attempting to model the aircraft icing environment, by defining means, variation, and extremes .

The data set was created by NOAA for Paul Shultz of the Forecast Systems Laboratory as part of a program to formulate and test icing forecast algorithms based on NGM model output. The data was described by P. Shultz and M. Politovich in "Toward the Improvement of Aircraft Icing Forecasts for the Continental United States (1992)." The article describes the PIREP data set which contains all icing PIREPs received by NOAA FSL between 13 March 1990 and 25 March 1991. Figure 9 (Shultz and Politovich, 1992) shows the location of all PIREPs reporting more than a trace of icing. Additionally, the article describes the distribution of PIREPs by aircraft type, time of day, day of the week, and day of the year.

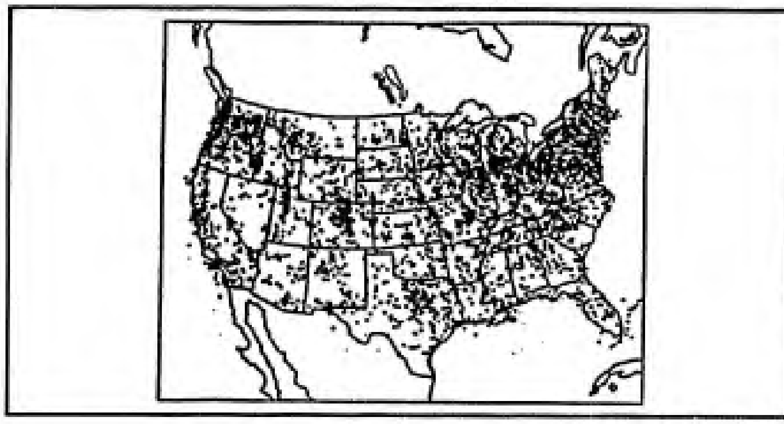


FIGURE 9, DISTRIBUTION OF TRACE OR GREATER PIREPS (after Shultz and Politovich, 1992)

The original data set was reduced by eliminating all PIREPs with missing information. The data were obtained from Dr. Shultz by Captain Dan Cornell (personal communication) of the USAF's Environmental Technical Application Center. Captain Cornell was comparing and verifying the computer codes of three separate aircraft icing forecast programs for the Air Force; one each from the Navy, Air Force, and the NWS. As part of Captain Cornell's study, the PIREPs data set was obtained from Dr. Shultz to verify the performance of the models. Captain Cornell explained through personal conversation that the data set was limited by spatial and temporal means for the ETAC study. Specifically, the study examined all PIREPs between 23 and 01z and 11 and 13z (within 1 hour of RAOB ascent) and within 50 miles of a sounding location. This sort reduced the data set to 728 pireps. After obtaining the corresponding soundings to these PIREPs, Captain Cornell had the data needed to verify the model forecasts. The sounding were used to verify the computer grid point data and the PIREPs could confirm the accuracy of the aircraft icing forecasts. This verification data produced by Dan Cornell created a unique opportunity to analyze remotely sensed parameters with a verified icing type and severity.

After consulting with Captain Cornell, Dr. Jeck, and M. Politovich, a request was submitted for the PIREPs data set sorted by icing type and intensity. Atmospheric soundings corresponding to the PIREPs were matched to the data, and were then interpolated to the individual PIREPs to produce parameters at the same height and then merged with the PIREPs to produce a data set with 728 confirmed aircraft icing reports in the following columns: Year / Month / Day / Latitude / Longitude / Station WMO number / Temperature / Relative Humidity / Dew Point Temperature / Lapse Rate / Dew Point Spread / Potential Temperature Change / NGM Modeled Vertical Velocity / NGM Modeled Relative Humidity / NGM Modeled Temperature / Aircraft Type / Icing Type / Showalter Index / and Icing Intensity. Unfortunately a few of the parameters were not always available. These included; potential temperature change, NGM modeled vertical velocity, and aircraft type. Table 1 contains the type, month by total number and percentage, and the time of the PIREP in the original data set.

TABLE 1, Distribution of Original PIREPs by Month, Type, and Time

Distribution of Original PIREPs by Month, Type, and Time												
Month	J	F	M	A	M	J	J	A	S	O	N	D
Total Number	118	47	214	79	59	25	16	04	11	17	65	90
Percent	16	6	29	11	8	3	2	1	.5	2	9	12
Rime Cases	55	22	89	40	25	09	09	01	07	11	35	39
Clear Cases	33	08	34	15	18	08	04	03	02	03	12	20
Mixed Cases	30	17	91	24	16	08	03	00	02	03	18	31

Type	Rime	Clear	Mixed
Number of Cases	334	161	233
Percentage	45	22	32

Time	00z	12z
Number of Cases	456	272
Percentage	63	37

While the climatology of aircraft icing is not the purpose of this paper, the locations of the PIREPs is discussed briefly. Appendix B contains Tables and Figures of the PIREP distribution. The PIREPs used in this study were distributed throughout the Continental United States (CONUS) and showed good spatial representation with Figure 24 containing 53 of 72 sounding location. Table 31 shows the total number of icing reports at each sounding location and the number of reports by the three icing types. Table 32 contains the the number of icing reports by intensity. Figure 30 is interesting as it shows the sounding locations not represented in this study, most notably Denver. The sounding locations not represented in this study are listed in Table 33. With regard to icing intensity while aircraft icing can occur throughout the CONUS, the probability of more adverse icing increases toward the north and in proximity to water bodies (i.e. dicussion in AWS TR80/001, 1980). The spatial distribution of the icing reports analyzed in this study is not suprising considering the climatology for the occurence of clouds containing supercolled water droplets. This climatology is depicted in Figure 10.

FIGURE 10, December-January-February Percent Frequency of Occurence of Supercooled Stratus and Low Cumulus (Talbot, personal communication)

Figures 27 to 29 reaffirm this trend and draw attention to that with increased intensity, the occurre: ce of icing occurs in the Pacific Northwest and near the Great Lakes region.

After examination of the data set, it was evident that there were PIREPs indicative of localized icing conditions, those reports with a temperature above 0°C and relatively large dew point spreads. Despite limiting the distance between the PIREPs and the soundings to 50 miles, there were PIREPs where it appeared that the plane was in icing conditions in cloud and the sounding was in a dry region. After consultation with numerous people in the field, all PIREPs with a temperature of above 0°C or dew point spreads of 9°C or greater were removed. Table 34 in Appendix B shows the location of the icing PIREPs removed and tables containing statistics on these PIREPs are located at the back of this paper. This removed 90 PIREPs and reduced the data set to 638 PIREPs . While all PIREPs with a temperature larger than 0°C were removed, a note should be made about this procedure. A relevant paper by Byers (1944) discussed the difference in the latent heats of evaporation and of fusion. He cited the example of liquid water on an aircraft surface while in the presence of ice crystals at -10°C. It would require sufficient energy in evaporating 12 percent of the liquid mass, that the remaining 88 percent would freeze. Thus the difference in the latent heats of evaporation and of fusion may produce aircraft icing at temperatures warmer than 0°C.

Since over 12 percent of the original data set was removed, the statistics from these removed data are summarize in Appendix C. Tables 38 to 42 show the mean, variation and extremes of the data removed. The monthly distribution of these PIREPs resembles the original and revised data sets with spring the most frequent season followed by winter; March was the most frequent month for PIREPs followed by January. There was a higher percentage of PIREPs removed from the summer months, and December had the highest percentage (18.8 percent) of PIREPs removed from the original data set. July was second most affected month with 16 percent removed. The three types of aircraft icing were removed in equal proportions except for a slightly higher percentage for the mixed ice reports. The most significant change to occur was the distribution of PIREPs by time and this can be seen in Table 37. Three quarters of the PIREPs removed were in the early evening at 00z. This supported the premise that convective scenarios could be contributing to the large dew point spreads in the data set (i.e. the plane was in cloud while nearby the sounding ascended through dry air).

The reduction of the data set produced the statistics in Table 2, which show the original mean, variation and extreme values; the statistics from the new data set, and the statistics from the data removed. These results can be used to ascertain the net result of the removal of the 90 PIREPs . Essentially the removal of these data produced a warmer, more moist data set with little change to the lapse rate. The average dew point spread of the removed PIREPs was extremely high when compared to the original mean dew point spread and the average relative humidity was relatively low.

After removing the non-representative reports, an analysis revealed that nearly one half of the PIREPs used in this study (47 percent) occurred in the spring (March to May) season with 27 percent of the PIREPs occurring in the month of March. The distribution of PIREPs by month is shown in Table 3 by the total number of PIREPs occuring in each month, the percentage of the data set reported by month, and the number of each of the three types of icing per month. The high number of PIREPs in the month of March can be explained partially by the one week overlap in NOAA's 53 week study (Shultz and Politovich, 1992). Winter (December to February) was the second most frequent season for the PIREPs studied in this research with over a third (34.6 percent). January was the second most frequent month for the icing reports and the low percentage of occurrence in February (6 percent) was attributed to unusually dry conditions for that month in 1991. As would be expected, summer (June to August) was the season of lowest frequency (5.6 percent). The trends for each icing type were consistent with the findings of the entire data set. Roughly one-half of the PIREP icing types were Rime (Table 4) and 60 percent of the icing reports studied in this paper were observed in the evening soundings (00z), which can be correlated with the heavier traffic present at that time of day (Table 5). One last point, while the data collected by NOAA was for the period from 13 March 1990 to 25 March 1991, 289 PIREPs studied in this paper were from the period from 1 January to 25 March 1991. The remaining 389 PIREPs were from 1990.

TABLE 2, Comparison of Original, Used, and Removed PIREPs

Temperature Comparison (°C)				
Statistic	Maximum	Minimum	Mean	Deviation
Original PIREPs	3.6	-34.5	-8.89	6.82
PIREPs Used	0	-34.5	-8.70	6.43
PIREPs Removed	3.6	-32.4	-10.66	8.99
Relative Humidity Comparison (Percentage)				
Statistic	Maximum	Minimum	Mean	Deviation
Original PIREPs	98.8	3.5	77.22	21.46
PIREPS Used	98.8	51.5	84.16	10.33
PIREPs Removed	69.0	3.5	28.15	14.95
Dew Point Temperature Comparison (°C)				
Statistic	Maximum	Minimum	Mean	Deviation
Original PIREPs	9.0	-62.4	-13.10	9.49
PIREPs Used	-0.1	-39.1	-10.94	6.94
Removed PIREPs	9.0	-62.4	-28.41	11.0
Environmental Lapse Rate Comparison (°C/1000 Feet)				
Statistic	Maximum	Minimum	Mean	Deviation
Original PIREPs	4.2	-12	1.3	1.53
PIREPs	4.2	-12	1.3	1.58
Removed PIREPs	3.2	-3	1.28	1.12
Dew Point Depression Comparison (°C)				
Statistic	Maximum	Minimum	Mean	Deviation
Original PIREPs	30	0.10	4.21	5.95
PIREPs	8.7	0.10	2.30	1.70
Removed PIREPs	30	9	17.75	7.54

TABLE 3, Distribution of Icing PIREPs by Month

Month	J	F	M	A	M	J	J	A	S	O	N	D
Total Number	107	40	171	71	55	21	11	04	11	15	58	74
Percent	17	06	27	11	09	03	02	01	02	02	09	12
Rime Cases	52	18	74	35	24	09	04	01	07	10	31	34
Clear Cases	28	06	28	14	16	07	04	03	02	03	11	18
Mixed Cases	27	16	69	22	15	05	03	00	02	02	16	22

TABLE 4, Distribution of Icing PIREPs by Type

Type	Rime	Clear	Mixed
Number of Cases	299	144	199
Percentage	47	22	31

TABLE 5, Distribution of Icing PIREPs by Time

Time	00z	12z
Number of Cases	389	249
Percentage	60	40
Rime Cases	178	121
Percentage	60	40
Clear Cases	84	56
Percentage	60	40
Mixed Cases	127	72
Percentage	64	36

An interesting note on the statistics of the icing parameters should be made here. The mean value for the Rime icing type occurred on the opposite side of the total mean with respect to the Clear icing type (i.e., the mean temperature for Rime type icing was colder than the total mean, while the mean temperature for Clear type icing was warmer than the total mean temperature). Secondly, the standard deviation of the Mixed ice parameter was always smaller than the standard deviation of the total, Rime and Clear parameters, defining a relatively smaller regime for Mixed aircraft ice. Lastly, with the exception of the lapse rate, the mean of the Mixed ice parameter occured on the side of the total mean where more a severe icing intensity is usually expected (i.e., slightly warmer than the mean modeled and actual temperature, a higher modeled and actual relative humidity, a lower dew point and dew point spread, and a more unstable Showalter's index). This helps to defines Mixed icing as a relatively more dangerous type of aircraft icing than simply a mixture of Clear and Rime ice.

Figure 11 and Tables 6 and 7 show the analysis of temperature from the icing PIREPs. Rime icing occured at a colder temperature than Clear icing did. The Clear ice histogram shows this with the peak temperature at -3 °C. The tables contain the extreme values, the mean and standard deviation. Rime icing severity increases with decreasing temperature, Clear icing severity increases with decreasing temperature, and moderate Mixed icing displayed the lowest standard deviation. These findings were expected, since in World War II (Byers 1944) it was observed that large droplets were not numerous at colder temperatures as small droplets. This confirmed the occurrence of Rime type icing, defined by their relatively smaller droplets, at colder temperatures and Clear type icing at relatively warmer temperatures.

TABLE 6, PIREP Temperature Analysis by Type (°C)

Statistic	Maximum	Minimum	Mean	Deviation
All PIREPs	0.0	34.5	-8.70	6.43
Rime PIREPs	0.0	-34.5	-10.1	6.58
Clear PIREPs	0.0	-33.1	-7.30	6.85
Mixed PIREPs	0.0	-27.5	-7.50	5.34

TABLE 7, PIREP Temperature Analysis by Intensity (°C)

Statistic	Maximum	Minimum	Mean	Deviation
Trace Rime	0.0	-29.3	-8.92	6.01
Light Rime	0.0	-34.5	-10.9	6.93
Moderate Rime	-0.4	-29.8	-11.2	6.73
Trace Clear	0.0	-15.6	-5.38	3.92
Light Clear	-0.1	-33.1	-9.98	8.67
Moderate Clear	-0.4	-14.1	-3.95	4.50
Trace Mixed	0.0	-27.4	-6.41	5.43
Light Mixed	-1.3	-27.5	-8.64	5.36
Moderate Mixed	-3.1	-7.03	-7.03	2.38

Higher relative humidities were found for Rime type icing reports than Clear type icing, which reflected a relatively moister layer in the atmosphere producing stratiform clouds and Rime icing while the Clear type ice appeared to be occuring in a more convective environment. The PIREPs results (Figure 12 and Tables 8 and 9) showed an increased relative humidity and smaller standard deviation with increased icing severity for both Rime and Clear icing. While the mean relative humidity was 84 percent, Figure 14 indicated that the optimal range was from 85 to 90 percent.

TABLE 8, PIREP Relative Humidity Analysis by Type (Percentage)

Statistic	Maximum	Minimum	Mean	Deviation
All PIREPs	98.8	51.5	84.16	10.3
Rime PIREPs	98.1	51.6	84.45	9.98
Clear PIREPs	95.9	51.5	81.89	11.8
Mixed PIREPs	98.8	53.7	85.37	9.50

TABLE 9, PIREP Relative Humidity Analysis by Intensity (Percentages)

Statistic	Maximum	Minimum	Mean	Deviation
Trace Rime	96.5	51.6	83.73	10.8
Light Rime	98.1	53.0	84.42	9.94
Moderate Rime	96.4	65.9	86.33	7.50
Trace Clear	95.9	51.5	82.60	11.7
Light Clear	93.3	53.5	79.79	11.9
Moderate Clear	92.9	87.1	91.66	1.87
Trace Mixed	96.6	55.6	86.88	8.89
Light Mixed	98.8	53.7	83.88	10.3
Moderate Mixed	91.7	72.6	84.66	6.40

Colder dew point temperatures occurred with Rime type icing reports and are displayed in Figure 13 and Tables 10 and 11. The mean values for increased icing severity showed no definitive trends but Figure 13 does indicate that Clear does not occur as frequently at low temperatures. The standard deviation for Mixed icing reports once again was the smallest for the three types. The dew point depressions derived from these temperatures were larger than expected and can be attributed to both the convective nature of the Clear and Mixed type icing and to the lack of accuracy of the moisture sensor of the RAOB in saturated conditions.

TABLE 10, PIREP Dew Point Temperature Analysis by Type (°C)

Statistic	Maximum	Minimum	Mean	Deviation
All PIREPs	-0.1	-39.1	-9.55	6.94
Rime PIREPs	-0.1	-39.1	-12.32	7.12
Clear PIREPs	-0.1	-37.2	-9.96	7.73
Mixed PIREPs	-1	-31.1	-9.55	5.58

TABLE 11, PIREP Dew Point Temperature Analysis by Intensity (°C)

Statistic	Maximum	Minimum	Mean	Deviation
Trace Rime	-0.7	-32.8	-11.26	6.57
Light Rime	-0.1	-39.1	-13.14	7.47
Moderate Rime	-1.4	-33.1	-13.07	7.35
Trace Clear	-0.1	-18.6	-7.93	4.91
Light Clear	-1.1	-37.2	-12.96	9.52
Moderate Clear	-1.4	-15.7	-5.07	4.68
Trace Mixed	-1	-31.1	-8.27	5.81
Light Mixed	-2.70	-30.4	-11.0	5.57
Moderate Mixed	-1.20	-15.3	-8.75	3.00

In Tables 12 and 13, Rime type icing is shown to occur in less stable air than Clear icing. This result was unexpected since Rime occurs with smaller droplets in stratiform clouds and Clear icing generally in convective clouds. This contradictory result may be explained by the higher percentage of negative lapse rates, indicative of inversions, for the clear icing reports (17 percent) than for Rime (9 percent) or Mixed icing (10 percent) reports. The relatively large number of icing PIREPs with inversions present is partially addressed in an article by R. Rauber and A. Tokay (1991) in which the presence of supercooled water droplets near the top of clouds was discussed. Mixed icing PIREPs were more unstable than Rime as expected. Moderate Rime severity verses trace severity increased with stability. Increasing instability resulted in increasing Clear aircraft ice severity and with Moderate Mixed severity verses Trace Mixed ice. The mean sounding derived lapse rate was 1.3°C /1000 feet or 4.3°C/km. This result indicated that icing occurs in generally unstable conditions and was expected since upward vertical velocities are needed to create super-cooled cllouds Figure 14 graphically represents the sounding derived lapse rate.

TABLE 12, PIREP Sounding Derived Lapse Rate Analysis by Type (°C/1000 FT)

Statistic	Maximum	Minimum	Mean	Deviation
All PIREPs	4.2	-12	1.3	1.58
Rime PIREPs	4.2	-12	1.32	1.74
Rime PIREPs	3.4	-7	1.17	1.53
Mixed PIREPs	2.9	-5	1.36	1.35

TABLE 13, PIREP Sounding Lapse Rate Analysis by Intensity (°C/1000 FT)

Statistic	Maximum	Minimum	Mean	Deviation
Trace Rime	4.2	-12	1.1	2.13
Light Rime	4.2	-4	1.55	1.25
Moderate Rime	2.6	-7	1.35	1.61
Trace Clear	3.4	-7	1.26	1.64
Light Clear	2.8	-2	1.15	1.27
Moderate Clear	2	-5	0.44	2.25
Trace Mixed	2.9	-4	1.33	1.10
Light Mixed	2.8	-4	1.56	1.12
Moderate Mixed	2.7	-5	0.72	2.49

As with the trends in the relative humidity analysis, Clear icing displayed a less humid regime than Rime type icing. The mean dew point spread was lower and the standard deviation smaller for Moderate verse Trace severity in both Rime and Clear icing. The mean and standard deviation for Clear icing PIREPs was larger than for either Rime or Mixed ice PIREPs. A review of the Clear ice dew point spread data revealed many relatively large spreads and may be indicative of a convective environment. Figure 15 displayed results which were lost to an extent in the statistics. The histograms showed that the predominant dew point depression was 1°C.

TABLE 14, PIREP Dew Point Spread Analysis by Type (°C)

Statistic	Maximum	Minimum	Mean	Deviation
All PIREPs	8.7	0.10	2.30	1.70
Rime PIREPs	8.1	0.20	2.21	1.60
Clear PIREPs	8.7	0.60	2.71	1.97
Mixed PIREPs	7.8	0.10	2.14	1.60

TABLE 15, PIREP Dew Point Spread Analysis by Intensity (°C)

Statistic	Maximum	Minimum	Mean	Deviation
Trace Rime	8.1	0.50	2.34	1.75
Light Rime	7.80	0.20	2.22	1.62
Moderate Rime	5.10	0.40	1.83	1.05
Trace Clear	8.70	0.60	2.65	2.02
Light Clear	8.20	1	2.99	1.94
Moderate Clear	1.60	1	1.12	0.20
Trace Mixed	7.50	0.40	1.86	1.44
Light Mixed	7.80	0.10	2.36	1.78
Moderate Mixed	5.20	1.10	2.31	1.19

The modeled NGM temperature statistics in Table 16 and 17 resembled the trends revealed by the remotely-sensed temperatures, with the Rime ice mean warmer than the Clear mean. Additionally, the NGM temperatures for both the total mean and the three types of ice were comparable to the sounding data. Figure 16 shows a broader temperature regime for the histogram than that depicted by Figure 11 for the RAOB based temperature. The histogram also shows a more distinct difference between the temperature for Rime and Clear type icing. The Rime reports showed a peak at -9°C while the Clear reports peaked at -3°C.

TABLE 16, PIREP NGM Temperature Analysis by Type (°C)

Statistic	Maximum	Minimum	Mean	Deviation
All PIREPs	4.7	-35.7	-8.74	6.46
Rime PIREPs	0	-35.7	-10.31	6.75
Clear PIREPs	0	-32.6	-6.92	6.45
Mixed PIREPs	4.7	-29.2	-7.63	5.38

TABLE 17, PIREP NGM Temperature Analysis by Intensity (°C)

Statistic	Maximum	Minimum	Mean	Deviation
Trace Rime	-0.1	-29.9	-9.01	6.06
Light Rime	0	-35.7	-11.35	7.26
Moderate Rime	-0.9	-29.2	-11.09	6.73
Trace Clear	0	-16.2	-4.93	3.57
Light Clear	-0.6	-32.6	-9.27	8.21
Moderate Clear	-2.6	-14.8	-5.74	3.93
Trace Mixed	4.7	-29.2	-6.84	5.55
Light Mixed	-0.6	-27.3	-8.74	5.32
Moderate Mixed	-0.4	-15.6	-6.13	4.15

As with the modeled temperatures, the analysis of the NGM modeled relative humidities, in Tables 18 and 19, produced results similarly to the observed data. Unlike the temperature data though, the mean modeled relative humidities were smaller than all sounding type and intensity means, ranging from five to ten percent lower than the observed data reflecting the dry bias of the NGM. This result helps to explain the low modeled relative humidities used in Shultz and Politovich's (1992) automated icing forecasts which were questioned by Forbes et. al (1993). Figure 17 shows a wider distribution of relative humdities for the icing reports, unlike the peak at 90 percent in Figure 12 from RAOB relative humidities. The peak occured at 80 percent and a distinct peak at 75 percent for Rime and Clear Type icing relative humidities, respectfively.

TABLE 18, PIREP NGM Relative Humidity Analysis by Type (Percent)

Statistic	Maximum	Minimum	Mean	Deviation
All PIREPs	99.2	40.9	77.08	12.0
Rime PIREPs	97.5	40.9	76.89	12.5
Clear PIREPs	99.2	43.9	77.92	11.5
Mixed PIREPs	99.2	40.9	77.40	11.8

TABLE 19, PIREP NGM Relative Humidity Analysis by Intensity (Percent)

Statistic	Maximum	Minimum	Mean	Deviation
Trace Rime	97.0	45.8	75.73	13.61
Light Rime	96.6	40.9	76.56	11.60
Moderate Rime	97.5	49.2	80.40	11.08
Trace Clear	98.1	55.1	77.12	9.760
Light Clear	98.2	45.2	78.32	12.41
Moderate Clear	99.2	43.9	81.47	16.89
Trace Mixed	94.8	48.5	78.24	10.68
Light Mixed	99.0	41.4	76.11	13.08
Moderate Mixed	88.3	61.9	74.07	8.130

The analysis of Tables 20 and 21 and Figure 18 for the Showalter's Index revealed the same patterns exhibited from examination of the environmental lapse rate. The index mean obtained from Rime type icing reports was larger, indicating a more stable atmosphere, than the index mean of the Clear icing type PIREPs. The results obtained from the Showalter's index help confirm the premise made in the lapse rate section, when the large number of inversions were believed to skew the Clear ice mean. Figure 20 shows the more unstable conditions correlate with Clear icing, as would be expected.

TABLE 20, PIREP Showalter Index Analysis by Type

Statistic	Maximum	Minimum	Mean	Deviation
All PIREPs	37.2	-2	9.08	6.43
Rime PIREPs	27.5	-1.5	9.23	6.48
Clear PIREPs	37.2	-2	8.88	7.04
Mixed PIREPs	25.1	-0.9	8.99	5.89

TABLE 21, PIREP Showalter Index Analysis by Intensity

Statistic	Maximum	Minimum	Mean	Deviation
Trace Rime	26.3	-0.2	9.31	6.60
Light Rime	27.5	-1.5	9.07	6.04
Moderate Rime	25.2	-1.1	9.41	7.29
Trace Clear	23.4	-2	7.63	6.41
Light Clear	37.2	-1.3	10.38	7.62
Moderate Clear	21.8	-2	8.54	6.19
Trace Mixed	25.1	-0.9	8.44	5.89
Light Mixed	19.8	-0.1	8.72	5.18
Moderate Mixed	23.2	-0.1	12.09	7.60

Table 22 and 23 and Figure 19 were added to show the mean height of the icing PIREPs, and that Rime type icing occurred at a higher altitude than Clear icing in this data. Mixed icing occurred at a height between the other two types and once again had the lowest standard deviation of the three types. The histogram in Figure 19 showed fewer Clear icing reports at the higher altitudes.

TABLE 22, PIREP Height Analysis by Type (Feet)

Statistic	Maximum	Minimum	Mean	Deviation
All PIREPs	28000	4000	11356	5209
Rime PIREPs	28000	4700	12001	5490
Rime PIREPs	27000	4500	10684	5075
Mixed PIREPs	26000	4000	10789	4724

TABLE 23, PIREP Height Analysis by Intensity (Feet)

Statistic	Maximum	Minimum	Mean	Deviation
Trace Rime	26000	4700	11326	5280
Light Rime	28000	4700	12373	5571
Moderate Rime	25000	4800	12448	5692
Trace Clear	27000	4500	9775	4358
Light Clear	26000	5000	12073	5558
Moderate Clear	20000	5000	8428	5711
Trace Mixed	22000	4800	10664	4606
Light Mixed	26000	4000	10756	4903
Moderate Mixed	20000	5000	11142	4518

VERIFICATION OF CURRENT AIRCRAFT ICING FORECAST RULES

After defining the aircraft icing environment, this thesis examined the PIREP data in an effort to verify the current forecast methods used in identifying aircraft ice accretion. Specifically in this study, the icing reports were used to validate forecast rules-of-thumb obtained from the Forecaster's Guide on Aircraft Icing (AWS 1980) and to verify an aircraft icing logic chart developed by D. Knapp and used experimentally at the USAF Global Weather Central. This study attempted to verify as many rules as possible with the PIREP data. Those rules not validated by the PIREPs have comments justified from the literature review. Guidance on forecasting the non-occurrence of aircraft icing (AWS 1980) is presented below:

Rule 1A. If the temperature is 0°C to -7°C and the dew point spread is greater than 2°C, forecast no icing with an 80 percent probability.

Rule 1B. If the temperature is - 8°C to -15°C and the dew point spread is greater than 3°C, forecast no icing with 80 percent probability.

Rule 1C. If the temperature is -16°C to - 22°C and the dew point spread is greater than 4°C, forecast no icing with 90 percent probability.

Rule 1D. If the temperature is colder than -22°C forecast no icing regardless of what the dew point spread is with 90 percent probability.

The results of the verification of Rule 1 (AWS 1980) are located in Table 24. Three of the four categories verified at over 80 percent of the time, with Rule 1B and 1D working more often than previously found by NACA. The non-occurrence of icing at a temperature from 0°C to -7°C with a dewpoint temperature spread of greater than 2°C verified in 71 percent of the cases. This relatively low percentage reflects the influence of Clear ice's convective regime and the lack of accuracy of the moisture sensor in the RAOB in conditions near saturation.

TABLE 24, Verification Percentages of the Non-Occurrence of Aircraft Icing

	Percentage of Cases Verified for each Forecast Rule			
Rule Analyzed	1A	1B	1C	1D
Rime PIREPs	69	89	83	94
Clear PIREPs	67	67	40	96
Mixed PIREPs	75	78	100	97
All PIREPs	71	82	83	96
	Percentage of PIREPs which Applied to each Rule			
Rule Analyzed	1A	1B	1C	1D
Rime PIREPs	41.1	40.5	12	5
Clear PIREPs	61.4	29.3	3.6	3.6
Mixed PIREPs	63.8	28.1	5.5	2.5
All PIREPs	52.7	34.2	8.2	3.9

Additionally, analysis of the PIREP data revealed that the temperature range and the dew point depression for the occurrence of icing could be reduced. The statistics verifying these rules below are in Table 25.

-No icing should be forecast with a temperature colder than -20°C. This represented 90 percent of the cases. This temperature has historical operational preference as it was common experience of WWII pilots to fly at temperature colder than -20°C to avoid icing as noted by Byers (1944).

-No icing should be forecast with a dew point spread greater than 3°C. This rule worked in 80 percent of the cases.

-No icing should be forecast with a dew point spread greater than 4°C. This rule worked in 85 percent of the cases.

TABLE 25, Verification Percentages Used to Reduce Icing Environment

Type of PIREPs	Rime	Clear	Mix	All
Temperature <-20°C	33	11	7	51
Percentage	89	92	96	92
Spread > 3°C	33	11	7	51
Percentage	89	92	96	92
Spread > 4°C	41	32	22	95
Percentage	86	77	96	85

The following rules apply to the type of icing.

Rule 10, Forecast rime icing when temperatures at flight altitude are colder than -15°C, or when between 0°C and -15°C in stable stratiform clouds.

Rule 11, Forecast clear icing when temperatures are between 0°C and -8°C in cumuliform clouds and in freezing precipitation.

Rule 12. Forecast mixed rime and clear icing when temperatures are between -9°C and -15°C in unstable clouds.

These rules were verified from temperature and stability analyses of the icing PIREPs. The statistics used to verify Rime type icing below -15°C are in Table 26. Table 26 also displays statistics from the examination of Rime icing colder than -13°C and -12°C, which shows that a more defined icing regime. Using a warmer temperature for the delineation for Rime type icing has also been suggested previously. Byers (1944) noted that larger droplets, which are associated with clear icing, were rare at temperature colder than -10°C. Specifically, he noted that for droplets not to be glaciated at temperature of -10°C or colder that condensation nuclei must be either rare or very small, inferring Rime.

When analyzing the PIREPs in the 0°C to -15°C regime, this study began by using the 2°C / 1000 feet (6.5°C / kilometer) lapse rate used at in the AFGWC experimental aircraft icing logic chart developed by D. Knapp. This produced positive results for the Rime PIREPs which occured in 84 percent of the cases as stable (less than or equal to 2°C). However, the results were disappointing for the Clear and Mixed PIREPs were verified at less than 13 percent for unstable conditions (greater than 2). The results were recomputed for lapse rates from 1°C to 2.2°C / 1000 feet to verify the PIREP occurrence of Rime, Clear, or Mixed. The results for lapse rates of 1.4°C to 2.0° C / 1000 feet are in Table 27. The optimum lapse rate appeared to be 1.6° C / 1000 feet (5.3°C / kilometer). Higher lapse rates for the delineation between stable/unstable conditions verified more Rime type cases while lower lapse rates showed more Clear and Mixed cases. The analysis was run a second time using a data set of PIREPs with temperatures from 0°C to -12°C for use with the proposed rule of forecasting Rime type icing with temperatures colder than -12°C. These results are in Table 28. The reduction of PIREPs with temperatures from -12°C to -15°C removed 41 Rime reports, 9 Clear icing reports, and 20 Mixed type icing reports. Across the top of Table 29 and 30 are the environmental lapse rate used for the stable / unstable delineation and underneath are the number and percentages of Rime type cases which were verified stable and Clear or Mixed cases which were verified as unstable. There is work being done currently on conditional stability and symmetric instability which may provide further insight to forecasting aircraft icing type. The results of this thesis support the following statements:

When considering Rime or Clear type icing, forecast Rime icing when the temperature is colder than -15°C. This occured in 80 percent of the cases. When considering Rime or Clear/Mixed type icing, forecast Rime. This occured in 63 percent of the cases. These percentages did not change for temperatures of -12°C and -13°C.

TABLE 26, Verification Data for the Rime Icing Environment

	PIREP Type			Rime Percentage	
Temperatures Analyzed	Rime	Clear	Mix	Rime/Clear	All
Colder than -15°C	55	15	18	79	63
Colder than -13°C	80	22	23	78	64
Colder than -12°C	96	24	35	80	62

TABLE 27, Stability Analysis for PIREPs with Temperatures from 0°C to -15°C

	Occurrence of Stable/ Unstable PIREPs						
Lapse Rate	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Rime PIREPs	83	95	119	138	159	177	193
Percent Stable	34	39	49	57	65	73	79
Clear PIREPs	76	70	61	50	45	37	31
Percent Unstable	61	56	49	40	36	30	25
Mixed PIREPs	122	109	101	94	80	65	55
Percent Unstable	67	60	56	52	44	36	30

TABLE 28, Stability Analysis for PIREPs with Temperatures between 0°C and -12°C

	Occurrence of Stable/ Unstable PIREPs						
Lapse Rate	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Rime PIREPs	69	81	104	121	136	150	166
Percent Stable	34	39	51	60	67	73	82
Clear PIREPs	69	63	57	46	41	33	29
Percent Unstable	60	54	49	40	35	28	25
Mixed PIREPs	107	95	87	81	68	54	45
Percent Unstable	65	58	53	50	42	33	27

Occasionally the forecaster is forced to make a forecast from very little, or even no current data. Icing forecasts can be based on the percentages contained in figures obtained from AWS TN 80/001(1980). The frequencies suggested by AWS in this document for trace, light, or moderate icing are 87 percent, 12 percent, and 1 percent, respectively. The frequency by icing severity of the PIREPs examined in this study contradict these figures: the frequencies found for trace, light, or moderate icing were 45 percent, 43 percent, and 13 percent, respectively. The disparity of the occurence of icing severity between NACA's results and the results of this thesis are in part due to the fact that pilots frequently do not report trace icing (Jeck, personal communication).

Finally, the icing PIREP data set was used verify a logic chart produced by D. Knapp while he was in charge of the aircraft hazards modeling section at AFGWC. This chart is shown in Figure 20.

Icing Derived from Vertical Temperature and Dew Point Profile

MOIST LAYER TEMP RANGE °C	0>=T>-8				-8>=T>-16				-16>=T>=-22
$T-T_D$ °C	<=1		$1<T-T_D<=2$		<=1		$1<T-T_D<=3$		<=4
LAPSE RATE °C/1000 ft	<=2 STABLE	>2 UNST	<=2 STABLE	>2 UNST	<=2 STABLE	>2 UNST	<=2 STABLE	>2 UNST	N/A
ICING	LGT RIME	MDT CLR	TRACE RIME	LGT CLR	MDT RIME	MDT MXD	LGT RIME	LGT MXD	LGT RIME

FIGURE 20, Icing Derived from Vertical Temperature and Dew Point Profile (Knapp, personal correspondence)

The chart was verified for both the original chart and a modified chart were where the 2°C/1000 feet stability (6.5°C/km) delineation was replaced with a 1.6°C/1000 feet lapse rate (5.3°C/km). Tables 29 and 30 contains the percentages that the particular icing type, in row 1, and intensity, row 2, occurred in each section of the chart. Table is 29 is for a lapse rate differential of 2.0°C per 1000 feet and Table 30 is for the 1.6°C per 1000 feet lapse rate.

TABLE 29, Percentage Accuracy For D. Knapp's Original Chart

Temperature		0 to -8			8 to -16				<=22
Dew Point Spread	<=1		1-2		<=1		1-3		>= 4
Lapse Rate	<=2	>2	<=2	>2	<=2	>2	<=2	>2	
Correct Type	43	29	37	26	91	50	59	33	74
Correct Intensity	6	0	15	4	0	0	28	14	31

TABLE 30, Percentage Accuracy For D. Knapp's Revised Chart

Temperature		0 to -8			8 to -16				<=22
Dew Point Spread	<=1		1-2		<=1		1-3		>= 4
Lapse Rate	<=1.6	>1.6	<=1.6	>1.6	<=1.6	>1.6	<=1.6	>1.6	
Correct Type	61	30	47	31	100	57	74	33	74
Correct Intensity	7	6	20	7	0	0	33	19	31

The results of Table 29 and 30 were disappointing. While using a 1.6°C per 1000 feet lapse rate instead of a 2°C per 1000 feet lapse rate increased the number of cases predicted accurately by the chart, the overall performance of the chart did not display forecast skill (i.e. consistently performing above 50 percent) in this study. The lapse rate results are being incorporated in the forecast model at AFGWC and the initial results in the automated forecast procedure was encouraging.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

The results of this study compared favorably to those of NACA, who had previously collected aircraft icing data during the period from May 1952 to June 1955 and these data were studied at AWS. For that study, observations were made only when the aircraft was flying in stratiform clouds at air temperatures between 0°C and -32°C and which included a reported dew point. These data were analyzed to determine the relationships between temperature, dew point spread, and icing occurrence. Results of that analysis are shown in Figure 21 and in Figure 22. This research was unable to reproduce the same charts since NACA compared ice/no ice scenarios and this analysis used only PIREPs with a confirmation of icing. Figure 21 showed that the predominant temperature range for aircraft icing under these conditions was from -3°C to -7°C, while the data in this research showed 38 percent of the PIREPs reported temperatures in this range. In NACA's research, as the temperature became colder, the percentage of icing decreased. This study confirmed those results. Figure 22 showed the predominant dewpoint spread in NACA's study, irrespective of temperature, for aircraft icing under these conditions was 0°C, with the minimum at spreads of 7°C or more. The PIREPs studied in this paper showed a mean dew point spread of 2.3°C and a mode of 1°C. The difference of the two mean spreads arises from aircraft observed data being compared to remotely sensed data and the lack of accuracy of RAOB moisture sensor. The minimum spread reported by NACA was confirmed with 88 percent of the PIREPs in this study reporting a dew point spread smaller than 7° C. The results of the histogram (Figure 14) were more in line with NACA's results than the mean depression. Although icing intensities were not shown in Figure 22, 94 percent of cases of light icing occurred with a dew point spread < 2°C, and that all cases of moderate icing occurred with a zero dew point spread. D. Knapp's icing logic chart was based on these results. The dew point spreads analyzed in this report were not as small as those in NACA's study which can be partially attributed to the lack of accuracy in a saturated enviroment by the RAOB moisture sensor.

Frequency of Aircraft Icing by Air Temperature and Dew Point Spread

Frequency of Aircraft Icing by Air Temperature and Dew-Point Spread
(from observations having a dew-point report
made in stratiform clouds)

Air Temperature (°C)		Number of Observations	Number of Icing Cases	Percent Frequency of Icing
0 to -2	With spread = 0°	245	41	16.7
	With spread > 0°	49	8	16.3
	Total	294	49	16.7
-3 to -7	With spread ≤ 1°	1101	563	51.1
	With spread > 1°	114	37	32.5
	Total	1215	600	49.4
-8 to -12	With spread ≤ 2°	1018	418	41.1
	With spread > 2°	141	32	22.7
	Total	1159	450	38.8
-13 to -17	With spread ≤ 3°	1251	237	18.9
	With spread > 3°	133	15	11.3
	Total	1384	252	18.2
-18 to -22	With spread ≤ 4°	772	134	17.4
	With spread > 4°	77	7	9.1
	Total	849	141	16.6
-23 to -27	With spread ≤ 5°	347	38	11.0
	With spread > 5°	35	5	14.3
	Total	382	43	11.3
-28 to -32	With spread ≤ 6°	160	15	9.4
	With spread > 6°	20	0	0.0
	Total	180	15	8.3
Grand Total		5463	1550	28.4

FIGURE 21, Frequency of Aircraft Icing by Air Temperature and Dew Point Spread (taken from AWS, 1980)

Frequency of Aircraft Icing by Dew Point Spread Only

Frequency of Aircraft Icing by Dew-Point Spread Only
(from observations having a dew-point report
made in stratiform clouds at temperatures
between 0°C and -32°C)

Dew-Point Spread (°C)	Number of Observations	Number of Icing Cases	Percent Frequency of Icing
0	3565	1243	34.9
1	719	143	19.9
2	416	54	13.0
3	235	33	14.0
4	140	24	17.1
5	87	14	16.1
6	86	12	14.0
≥ 7	215	27	12.5
Grand Total	5463	1550	28.4

FIGURE 22, Frequency of Aircraft Icing by Dew Point Spread Only (AWS, 1980)

These results also agreed with the conclusions of Appleman (1954), and with the findings of the WADC during their flight testing. Appleman concluded that when temperature is plotted against dew point on a graph such as Figure 23, those observations of fog or cloud lying between the lines T = Td and T = 0.8Td represented cases of supercooled liquid water clouds and that in these cases icing was highly probable. This value was chosen to compensate for inaccuracies in radiosonde humidity measurements at subfreezing temperatures The results are presented in Figure 23. On this graph, the horizontal temperature axis (x-axis) is the zero degree dew point spread, and the line (T - Td) = -0.2 Td, which is equivalent form of T = 0.8 Td, is the heavy line running diagonally upward to the right from the origin (termed the "Appleman line").

Past statistics have suggested that the radiosonde measured, analyzed, or forecast dew point spread at flight level can be used as an indicator of aircraft icing occurrence. Considering only the dew point spread, in 84 percent of the cases there was no icing where the spread were greater than 3°C. In 80 percent of the cases there was no icing when the spread were less than 3°C. The results of this study compared favorably with those of NACA as 80 percent of the PIREPs displayed a dew point depression of 3°C or less. When compiling data, NACA found considerable scatter in the relation of icing occurrence to dew point spread. They subjectively selected a 3°C spread as a convenient dividing line between large probabilities of icing or of no icing and stated that experience indicates that a 4°C dew point spread might be a more operationally realistic division point. Once again the results of this study confirmed the results as 85 percent of the PIREPs displayed a dew point depression of 4°C or less and this study should be compared with Johannessen (AWS 1980) at AWS, in which it was found that at 500 mb a dew point spread of 4°C or less is indicative of the probable presence of clouds. A study by Cushman (AWS 1980) at AWS based on AWS weather reconnaissance data at 700 mb and 500 mb is also of interest. The dew point spread value which included most of the icing cases was found to range from 0° C at 0°C to 4°C at - 20°C. This general agreement with the NACA and Johannessen studies may be accidental since the correlation between reconnaissance measured dew point spread and radiosonde measured dew point spread is unknown; however, it is believed that for a statistical comparison, the mean radiosonde and reconnaissance data are compatible in this range of temperature and humidity. Therefore, for temperatures near -10°C to -15°C assume a dew point spread of 4°C or less should be indicative of clouds, and a spread of about 2°C or 3°C or less, should be indicative of probable icing.

Unfortunately the data set obtained for this research did not contain wind data. Aircraft icing intensities examined by a temperature sort and an analysis of veering and backing winds, with the respective advection, combined with could be used to verify these rules (AWS, 1980) if the dew point spread is 2°C or less at temperatures 0°C to -7°C, or is 3°C or less at -8°C to -15°C:

-In neutral or weak cold air advection, forecast trace icing with 75 percent probability.

-In zones of strong cold air advection, forecast light icing with 80 percent probability.

-In vigorous cumulus build up, forecast light icing with 90 percent probability.

The rules below need synoptic analysis to verify. Synoptic logic can be used to validate Rules 5 and 6; the area of icing with a warm front existing over a larger area than that of a cold front from indirect aerology of Norwegian methodology. A large amount of supercooled water droplets in the clouds can occur in a marked degree only in ascending air, therefore ice formation should be looked for mainly under such conditions and these conditions exist over a wider area for a warm front than for a cold front. Rules 8 and 9 can be inferred from the same logic. For freezing drizzle or rain to occur, supercooled water droplets are actually observed to be occurring. Since larger drops create more severe icing events (Politovich 1989), drizzle would be more severe than ordinary cloud droplets, and rain drops would create the most severe icing conditions (Stewart and King 1987). These rules are from AWS (1980).

Rule 3. Within clouds not resulting from frontal activity or orographic lifting:

-a. Over areas with steady non freezing precipitation, forecast little or no icing.

-b. Over areas without steady non freezing precipitation, particularly in cumuliform clouds, forecast light icing.

Rule 4. Within clouds resulting from frontal activity or orographic lifting, neither the presence nor absence of precipitation can be used as indicators of icing.

Rule 5. Within clouds up to 300 miles ahead of the warm front surface position, forecast light icing.

Rule 6. Within clouds, within 100 miles behind the cold front surface position, forecast moderate icing.

Rule 7. Within clouds over a deep, almost vertical, low-pressure center, forecast moderate icing.

Rule 8. In freezing drizzle, be low or in clouds, forecast moderate icing.

Rule 9. In freezing rain, below or in clouds, forecast severe icing.

The results of previous aircraft icing studies, and confirmed by this paper, show that while there are definitive areas where icing may occur, that there is no well defined enviroment. The RAOB data will enable the forecaster to predict a general area of occurence and a type of icing, but it appears that further improvement in the accuracy of aircraft icing forecast will not come from radiosonde data alone.

Some of the difficulties in forecasting or identifying hazardous icing conditions are clear. Many of the parameters important to the 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 relative humidity from the radiosonde are nonlinearly related to icing severity. Limitations in accuracy and resolution of these parameters result in over or under prediction of the severity. Finally the susceptibility of different aircraft types imply that a single icing hazard analysis will result in over or under prediction of the severity for other aircraft categories.

Given the limitations on the forecasting process, current techniques do a satisfactory job of 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) (Forbes, et al., 1993). 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 susceptibility of aircraft must be considered in their interpretation. Another problem is the 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 is the automated generation and transmission of PIREPS over digital data links. By the use of on-board ice sensors, automated continuous reporting of the presence or lack of icing conditions could be accomplished. If an adequate fleet of aircraft were equipped, a significant improvement in the forecasting and identification of hazardous icing conditions could be realized.

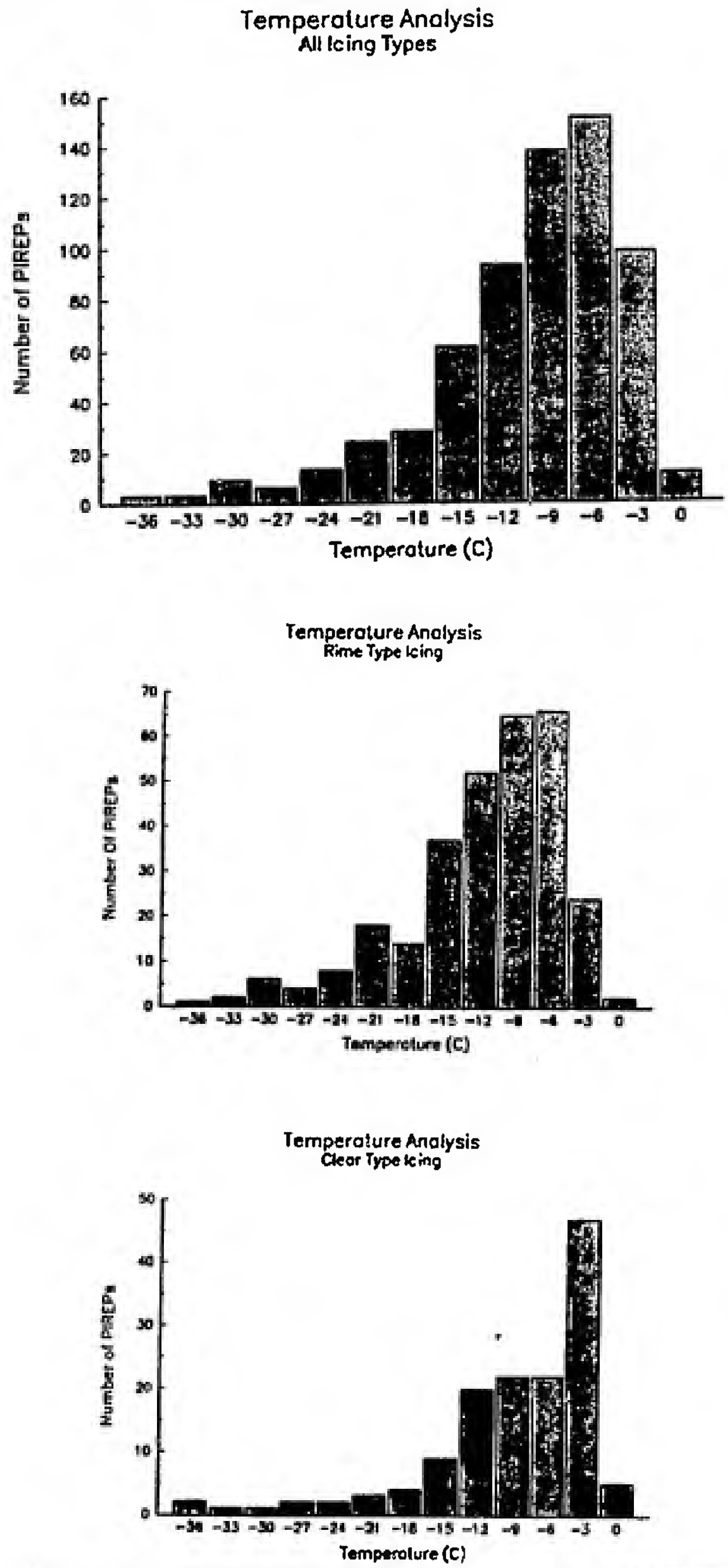
The severity of aircraft icing is found to be extremely sensitive to temperature, liquid water content and droplet size distribution particularly near regions of transition between rime and mixed icing conditions. The difficulty in measurement and the variability of these factors with altitude, position 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.

RECOMMENDATIONS

The first recommendation of this study was to incorporate the findings of this report into the forecaster's guide on aircraft icing. It would be extremely beneficial to distribute a revised aircraft icing guide back to the field forecatser's. Additionally a forecast checklist of the revised forecast procedures was recommended to be sent out to the field as this would increase the likelihood of the results being used. The results and the revised procedures were sent to NCAR and to AFGWC to be incorporated into automated forecasts.

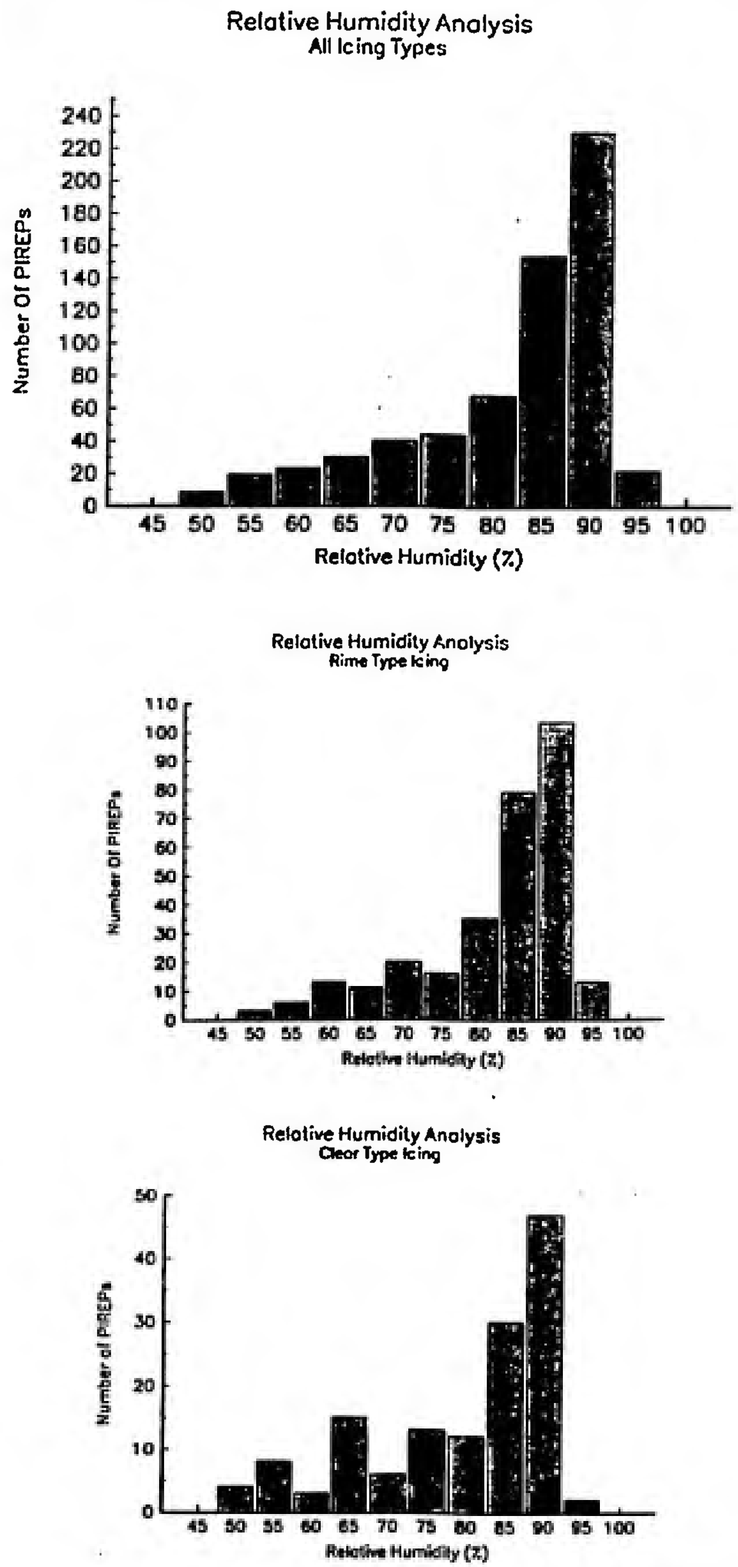
The study of radiosondes should only be the first step in evaluating the role of remotely sensed investigation of aircraft icing. The incorporation of NEXRAD data (Wilson, 1990) and the use of improved satellite data into the process would be significant improvement. Additionally a case study plotting PIREPs against surface synoptic features would validate the remaining forecast rules in forecasting procedure.

The last recommendation of this study was the encouragement to forecasters to solicit PIREPS. The accuracy of the forecast can be validated rather easily at the surface, but pilot reports are the only confirmation of the state of the atmosphere at flight level. Only sufficient and accurate reports from the users of the forecast product, can we validate the success of our service in providing aircraft icing forcasts.



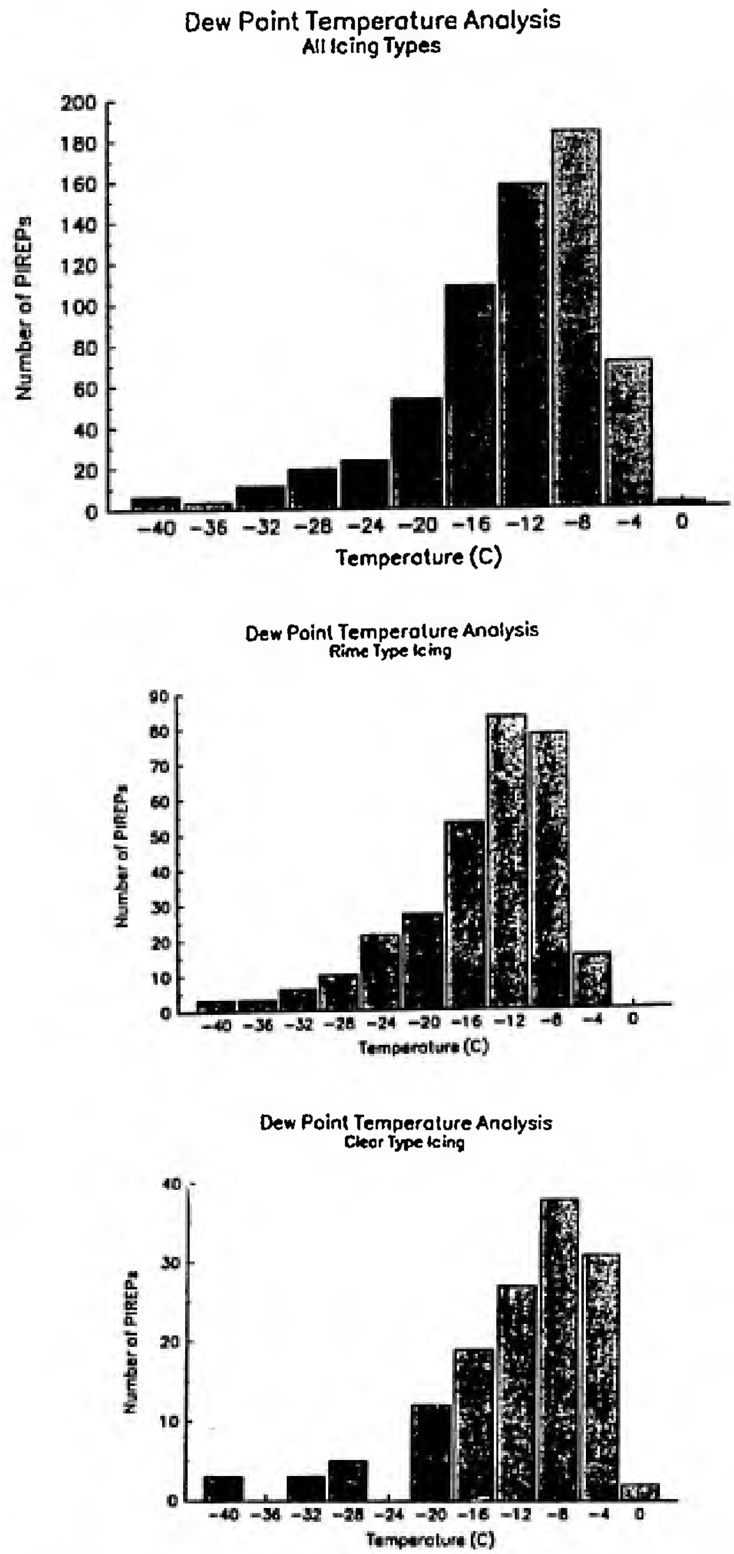
PIREP Temperature Analysis Histograms

FIGURE 11, PIREP Temperature Analysis Histograms



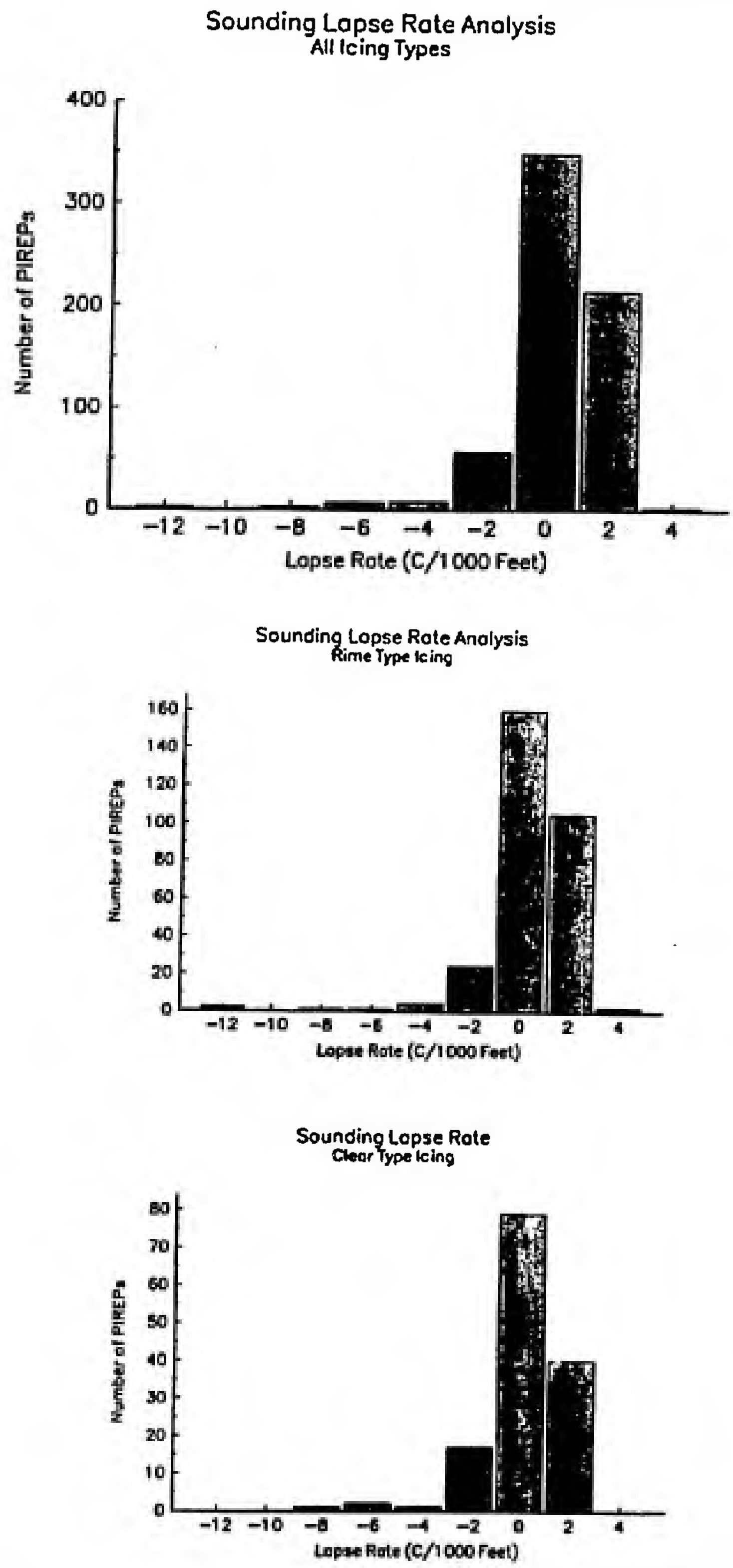
PIREP Relative Humidity Analysis Histograms

FIGURE 12, PIREP Relative Humidity Analysis Histograms



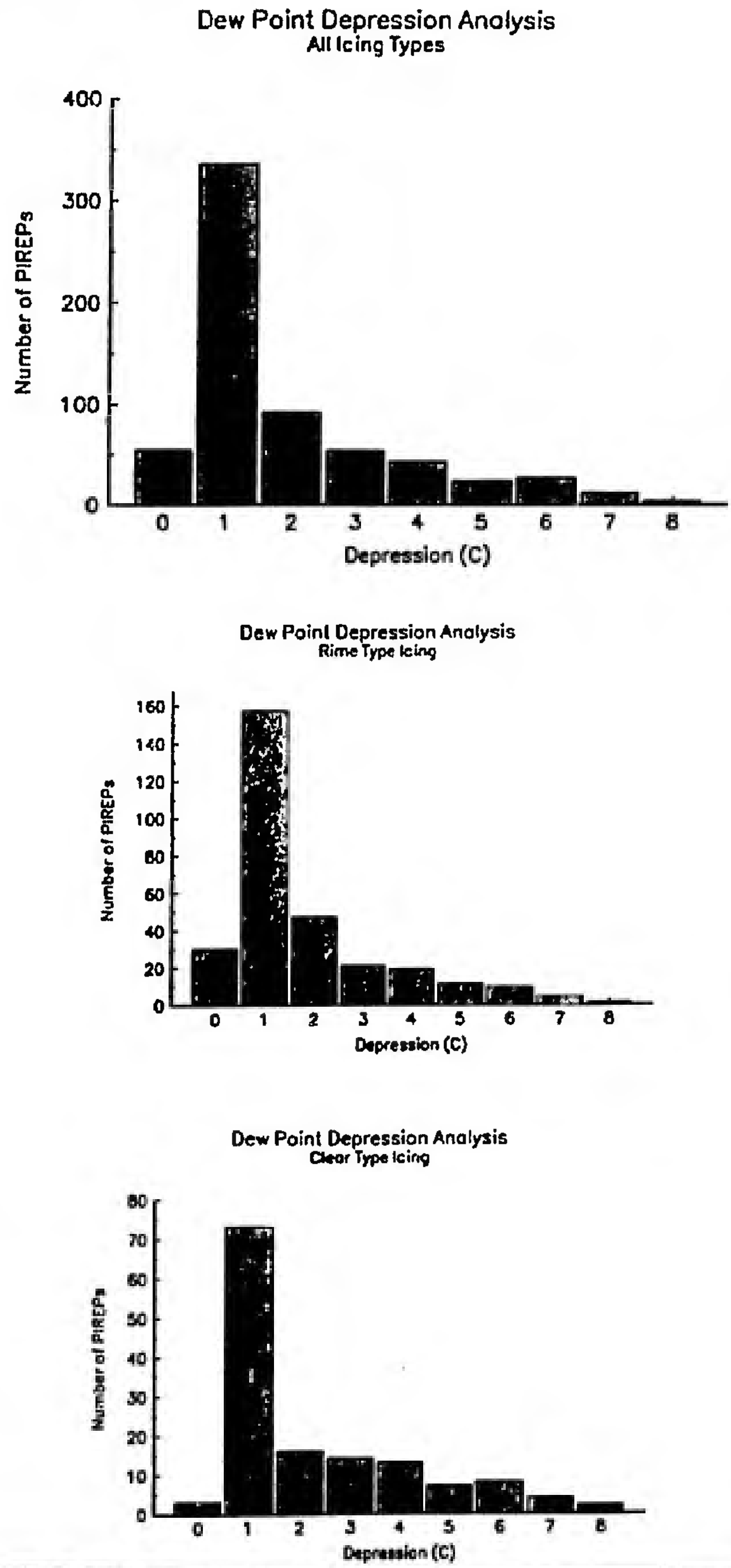
PIREP Dew Point Temperatue Analysis Histograms

FIGURE 13, PIREP Dew Point Temperatue Analysis Histograms



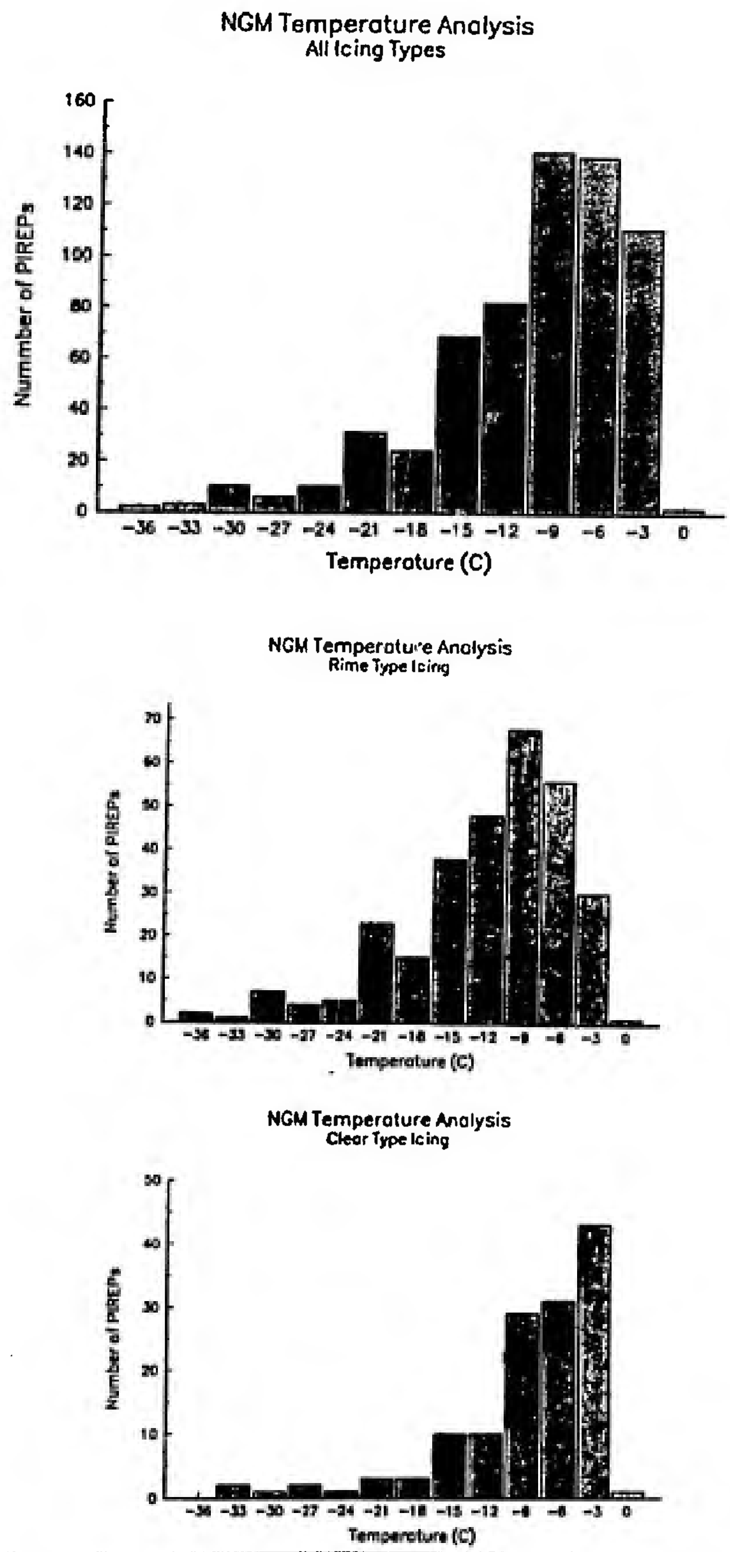
PIREP Sounding Derived Lapse Rate Analysis Histograms

FIGURE 14, PIREP Sounding Derived Lapse Rate Analysis Histograms



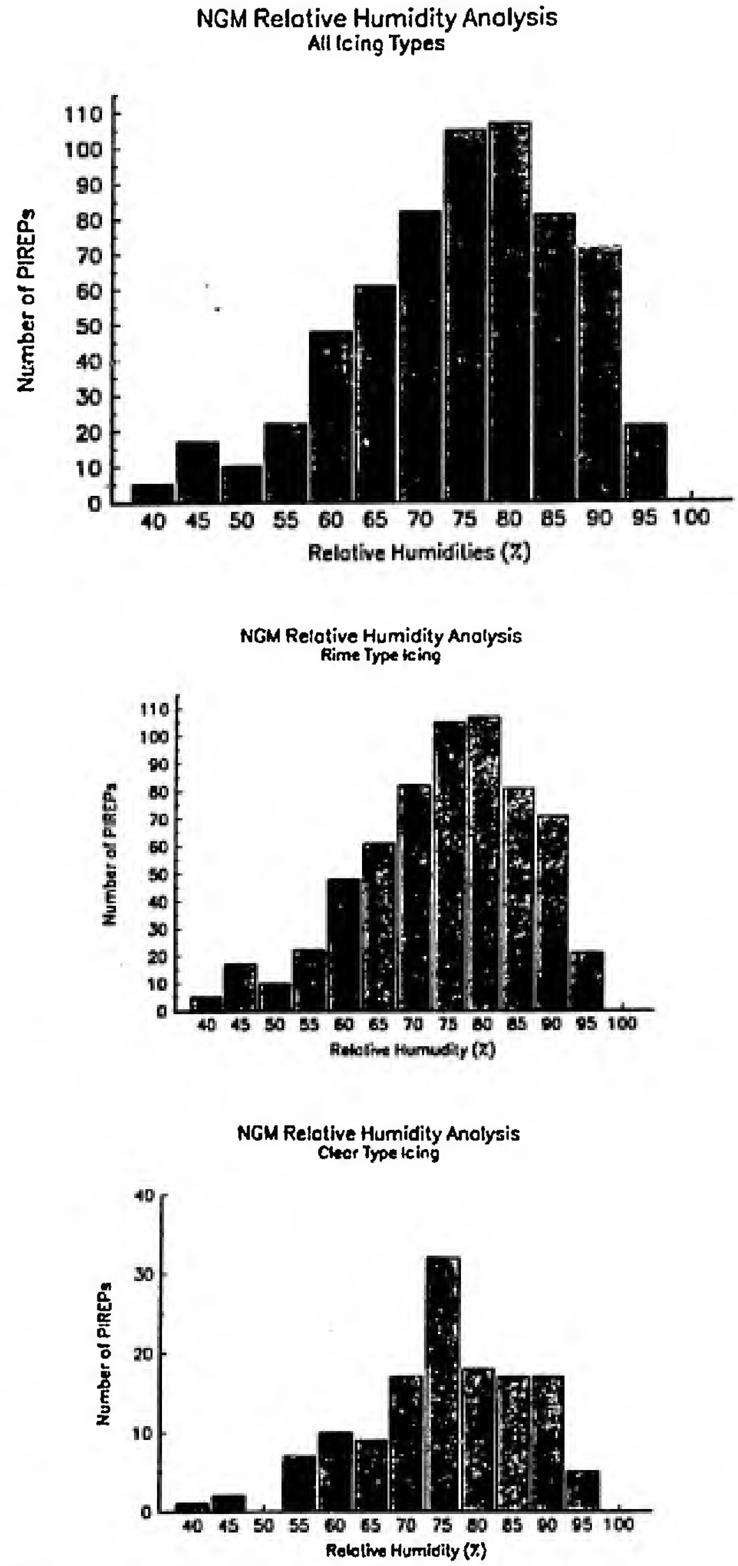
PIREP Dew Point Depression Analysis Histograms

FIGURE 15, PIREP Dew Point Depression Analysis Histograms



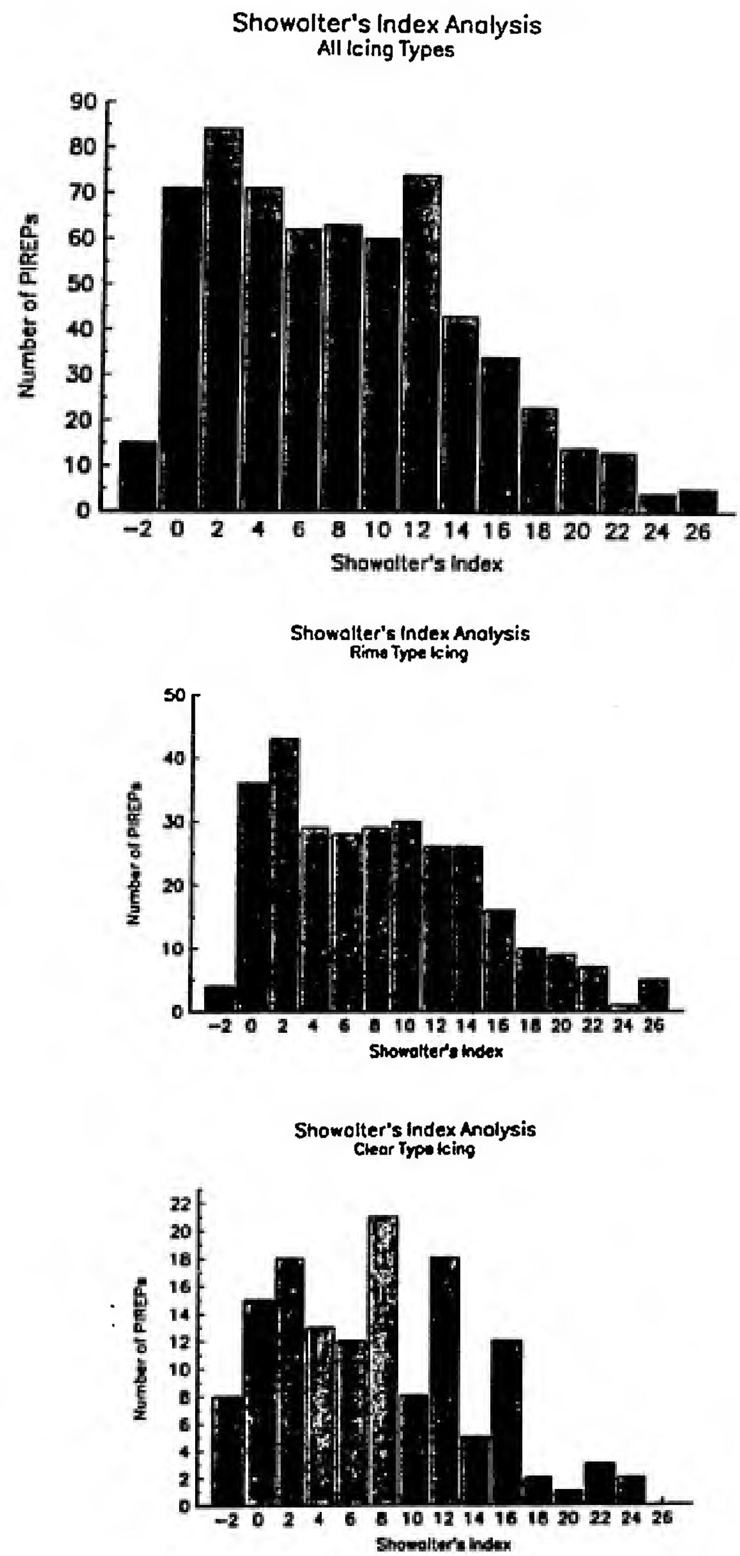
PIREP NGM Temperature Analysis Histograms

FIGURE 16, PIREP NGM Temperature Analysis Histograms



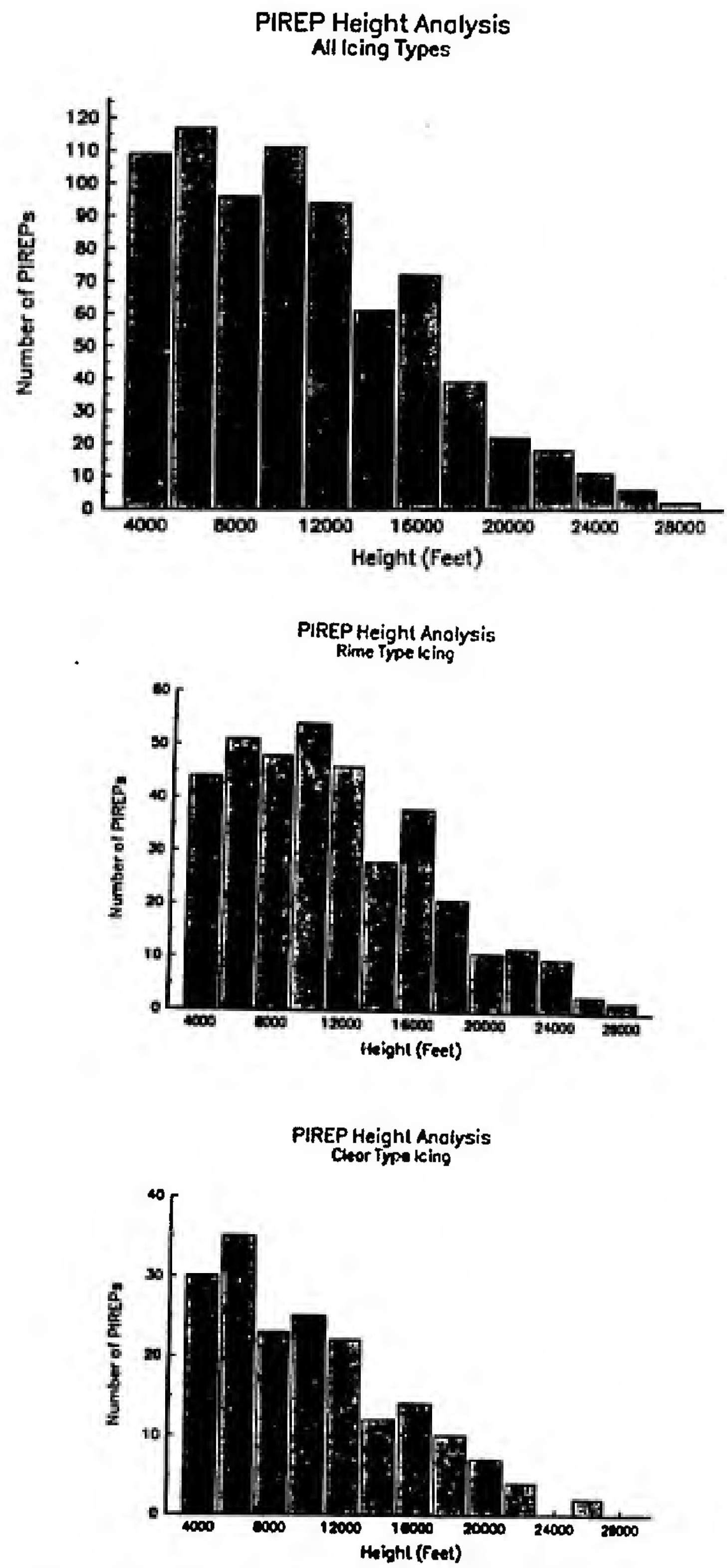
PIREP NGM Relative Humidity Analysis Histograms

FIGURE 17, PIREP NGM Relative Humidity Analysis Histograms



PIREP Showalter Index Analysis Histograms

FIGURE 18, PIREP Showalter Index Analysis Histograms



PIREP Height Analysis Histograms

FIGURE 19, PIREP Height Analysis Histograms

APPENDIX A

OUTLINE OF SUGGESTED PROCEDURES FOR FORECASTING AIRCRAFT ICING

OUTLINE OF SUGGESTED PROCEDURES FOR FORECASTING AIRCRAFT ICING

Icing forecasts are based upon observations of the atmosphere by several devices and grids of observation stations. The primary device is the rawinsonde, a balloon carried device which measures pressure (altitude); temperature; relative humidity; and, by tracking the device from ground, wind direction and speed. There are 72 rawinsonde stations in the upper air network in the contiguous 48 states. Although surface observations do not provide a direct measure of icing conditions aloft, they do provide sky conditions above a station and are the basis for the surface synoptic analysis.

Weather radar observes precipitation patterns are primarily used to identify areas of convective activity, but in certain circumstances it will identify rain, freezing rain, and snow. In some cases, it will show the freezing level as a "bright band," an altitude of strong return where frozen precipitation turns to rain. The development of Nexrad will significantly enhance the use of radar in identifying aircraft icing (Osborne, 1989; Wilson, 1990). Satellite photographs show cloud patterns from which storm and precipitation areas may be analyzed and infrared pictures measure the height of the cloud tops using temperature as an altitude indicator.

One of the best observations of icing conditions is the pilot report (PIREP) (Brown, et al., 1993; Forbes, et al., 1993)), a direct report of icing conditions which includes altitude, geographic location, the type of aircraft and the type and intensity of the icing. The problems with PIREPs are that they are made after the icing conditions have been encountered, they are not inclusive of all the pertinent airspace, and they are not made on a regular basis in terms of time (Ladwig, 1986; Brown, et al., 1993). Conversely, although spotty, the reports are most numerous in areas of heaviest traffic where they are most needed.

These observations are used directly by the forecaster in preparing icing forecasts. The forecaster analyzes these to determine known and probable areas and altitude ranges of icing in terms of "trace," "light," "moderate," or "severe." General icing forecasts are issued twice a day as part of the Aviation Area Forecasts issued by the National Weather Service (Biter, et al., 1993). Amendments to the forecast and warnings of situations that develop between forecast times are issued by in flight advisories in the form of SIGMETs (SIGgnificant METeorological information--an advisory of weather conditions possibly hazardous to all aircraft), convective SIGMETs, and AIRMETs (AIRman's METeorological information--an advisory of weather conditions possibly hazardous to light aircraft) which are issued any time a situation meets the definition of hazardous criteria or is forecasted. In the case of SIGMETs or AIRMETs, the issuance of a warning is based upon observed weather patterns derived extensively on the information from PIREPs. Convective SIGMETs are based upon radar observations.

Since aircraft icing results from the parameters of liquid water content, drop size distribution, and temperature and from the aerodynamic parameters of airfoil shape, airspeed, and configuration, a pilot must consider all of these parameters either directly or indirectly to evaluate the hazard. This would require in-flight weather forecasts in terms of the meteorological parameters. To use this information, the pilot has to determine the effect of the icing conditions on his particular aircraft. To enable the pilot to make this determination, manufacturers would have to test the aircraft under a wide range of these parameters and varying configurations and append this information to the aircraft's flight handbook, in the form of tables or nomograms, for the pilot's use.

To forecast any meteorological parameter, observations of the parameter must be made on a scale equal to or smaller than the scale of the forecasts. This is required both for the research to develop the forecasting techniques and to verify the forecasts once made. Currently, synoptic observations of liquid water content and drop size distribution are not made, and observations of temperature by rawinsonde are on a spacing that is marginal for a detailed analysis of many weather systems.

The few instruments available to measure liquid water content and drop size distribution are primarily used for research. Generally, they all have limitations; some will measure liquid water content but not drop size distribution, others are limited in the range of values measured, and are too complex and expensive for the number of observations required for synoptic use. The development of an inexpensive instrument to measure icing parameters over a wide range of values to describe hazardous conditions, and a means to expose the instruments on intervals which will allow a detailed synoptic analysis is needed. Several means to accomplish this include the addition of instruments to rawinsondes, the mounting of instruments on commercial aircraft, and the development of laser or microwave sensors which could probe cloud and precipitation areas from the ground.

The measurement and forecasting of the meteorological parameters associated with icing would be only the first of two parts of an improved icing forecasting system. The second part would be the evaluation of aircraft performance throughout a range of the meteorological parameters. This is being done to the extent necessary to meet the specifications of 14 CFR 25 for those aircraft certificated to fly into known icing conditions, but more data would be required to specify performance under specific icing conditions. The range of weather parameters would have to be expanded to include mixed ice crystals and water droplets and the large drop sizes encountered in freezing rain.

Forecasting aircraft icing must be considered rudimentary because of the complexity and scale of variation and the inadequate observations available. It would be desirable to develop a logical approach to the forecast from basic principles of meteorology, but this is a formidable task which has not yet been attempted. This section attempts to patch the data from icing studies into the forecast routine currently followed in the Air Force. Only experience and experimentation by forecasters will make the most of the information. Under these circumstances, icing forecasting performance will improve through following standard procedures to insure that significant factors are considered. Information has been consolidated into an outline. This outline comes from AWS (1980) and adds the results of this study.

Phase I: Preliminary Determinations. The first phase of the procedure in an icing forecast consists of the following. These are essential, regardless of the methods selected in the succeeding phases:

Clouds. Determine the present and forecast the future distribution, type, and vertical extent of clouds along the flight path. Clouds can be analyzed and forecast using information in surface observations, radiosonde observations, pilot reports, surface and upper air charts, using models, physical reasoning, and empirical studies. The influences of local effects should not be overlooked.

Temperatures. Determine segments of the flight path which will be in clouds colder than 0°C. An estimate of the freezing level can be made from the data contained in freezing level chart , constant pressure charts, radiosonde, reconnaissance, and AIREP observations, or by extrapolation from surface temperatures.

Precipitation. Check surface reports and synoptic charts for precipitation along the flight path, and forecast the precipitation character and pattern during the flight; special consideration should be given to the possibility of freezing precipitation.

Centrally Prepared Icing Forecasts. The Air Force Global Weather Central (AFGWC) and the National Weather Service (NWS) issues manually produced icing forecasts for the Northern Hemisphere for the layer from 10,000 to 55,000 feet. These forecasts are for the following time periods: 7 - 12 hours, 12 - 24 hours, 24 -36 hours, and 36 - 48 hours. Icing forecasts for 7 - 12 hours and 12 - 24 hours for the layer from the surface to 10,000 feet are produced for the contiguous United States (CONUS) and Europe. These forecasts are based on computer output of temperature, dew point, and stability for over 400 rawinsonde observations, computer forecasts of synoptic scale systems and the forecast rules in this report.

Phase II: Basic Icing Forecast. The second phase of the procedure is the preparation of the basic icing forecast. In this phase, the forecaster has a choice of three methods. Method 1 is the most sophisticated and will require the most time to use, especially if several prognostic soundings must be constructed. It is valid for icing in stratiform or cumuliform clouds, and yields forecasts of both the type and intensity of icing. Method 2 requires less time than Method 1, but is valid only for icing in stratiform clouds. It does not specify the intensity of icing. Method 3 consists of interpretation of the data available on a routine basis at weather stations by means of a number of forecasting rule, and does not require additional analysis. NOTE: Each method and forecast rule assumes that two basic conditions must exist; i.e., the surface of the aircraft must be colder than 0°C, and supercooled liquid water droplets, clouds or precipitation must be present in the flight path.

Method 1. Construct soundings or choose upwind soundings which are to be representative of conditions along the route at flight time. Check the stability at flight altitude as indicated by the lapse rate. Then forecast the type and probable maximum intensity of icing in those cloud areas which have temperatures colder than freezing from the chart shown in Figure 15, or a plastic overlay made from it. A concise summary of the instructions for use of the chart has been printed on Figure 15 and have shown promise in forecasting accuracy (Bernhardt 1989a).

Method 2. This method, which is limited to stratiform clouds, may be used if a lack of data or time precludes the use of Method 1. Determine the phase condition of stratiform clouds along the flight path using frost point considerations. The most practical procedure is to plot temperature and dew point from radiosonde data, reconnaissance data, pilot reports, or constant pressure charts, and read directly the likelihood of icing in stratiform clouds. This method does not specify the intensity of the icing. Under these conditions, the climatological frequencies for trace, light, and moderate icing are 87 percent, 12 percent, and 1 percent. It can be seen that this method is identical with that part of Method 1 concerned with determining the likelihood of rime icing irrespective of intensity.

Method 3. If a lack of data or time precludes the use of both Method 1 and Method 2, the empirical forecasting rules listed below can be used following a careful analysis of charts and reports available on display in the weather station.

(1). *Icing Intensity Forecasts from Upper Air Data.* Check upper air charts, pilot or reconnaissance reports, and radiosonde reports for the dew point spread at flight level, and check the upper air charts for the type of temperature advection along the route.

Rule 1. If the temperature is:

a. 0°C to -7°C, and the dew point spread is greater than 2°C, forecast no icing. There is an 80 percent probability of no icing under these conditions.

b. - 8°C to -15°C, and the dew point spread is greater than 3°C, forecast no icing with 80 percent probability.

c. -16°C to - 20°C, and the dew point spread is greater than 4°C, forecast no icing with 90 percent probability.

d. Colder than -20°C, forecast no icing regardless of what the dew point spread is with 90 percent probability.

Rule 2. If the dew point spread is 2°C or less at temperatures 0°C to -7° C, or is 3°C or less at -8°C to -15°C, in:

a. Zones of neutral or weak cold air advection, forecast trace icing with 75 percent probability.

b. Zones of strong cold air advection, forecast light icing with 80 percent probability.

c. Areas with vigorous cumulus build up due to insulated surface heating, forecast light icing with 90 percent probability.

(2) Icing Intensity Forecasts from Surface Chart Data. If upper air data and charts are not available, the conditions on the surface chart must be used as a guide for icing conditions, even though they are not as reliable as upper air. Check the surface charts for locations of the cloud shields of fronts, low-pressure centers, and precipitation areas along the route.

Rule 3. Within clouds not resulting from frontal activity or orographic lifting:

a. Over areas with steady non freezing precipitation, forecast little or no icing.

b. Over areas without steady non freezing precipitation, particularly in cumuliform clouds, forecast light icing.

Rule 4. Within clouds resulting from frontal activity or orographic lifting, neither the presence nor absence of precipitation can be used as indicators of icing.

Rule 5. Within clouds up to 300 miles ahead of the warm front surface position, forecast light icing.

Rule 6. Within clouds, within 100 miles behind the cold front surface position, forecast moderate icing.

Rule 7. Within clouds over a deep, almost vertical, low-pressure center, forecast moderate icing.

Rule 8. In freezing drizzle, be low or in clouds, forecast moderate icing.

Rule 9. In freezing rain (Stewart and King 1987), below or in clouds, forecast severe icing.

(3) *Icing Type Forecasts*. Rules 1 through 9 forecast occurrence and intensity of icing, but not the type, the following rules apply to the type of icing.

Rule 10. Forecast rime icing when temperatures at flight altitude are colder than -12°C, or when between -1°C and -12°C in stable stratiform clouds.

Rule 11. Forecast clear icing when temperatures are between 0°C and -8°C in cumuliform clouds and in freezing precipitation.

Rule 12. Forecast mixed rime and clear icing when temperatures are between - 9°C and -12°C in unstable clouds

. (4) Forecasting from Extremely Limited Data. Occasionally the forecaster is forced to make a forecast from very little, or even no current data. Assuming ice will occur, the frequencies for trace, light, or moderate icing are 87 percent, 12 percent, and 1 percent, respectively.

Phase III: Modification of the Basic Icing Forecast. The final phase of the procedure is modification of the icing forecast that was obtained in Phase II. This is essentially a subjective process, and rules cannot be laid down. The forecaster should consider the following: Intensification or weakening of features, such as low pressure centers, fronts, and squall lines during the time between the latest synoptic data and the forecast time; local influences, such as location, terrain features, and ocean coastlines or lake shores; radar observations; pilot reports of icing; etc. The forecaster should not intentionally over forecast or underforecast the amount (duration) and intensity of aircraft icing. An over forecast results in the aircraft's payload being decreased because of increased fuel; while an underforecast might result in an operational emergency.

APPENDIX B

THE SYNOPTIC DISTRIBUTION OF THE ICING PIREPS USED IN THIS STUDY

THE SYNOPTIC DISTRIBUTION OF THE ICING PIREPS USED IN THIS STUDY

While it was not the intention of this paper to review the climatology of aircraft icing, the locations of the PIREPs, with regard to the upper air station used is discussed briefly in this appendix. The PIREPs were distributed throughout the CONUS and relatively uniform representation; 53 of the 72 sounding locations were used, of the upper air network was utilized. Figure 24 shows the RAOB locations used in the thesis. While aircraft icing can occur throughout the CONUS, icing occurrence is more likely in the northern regions and in proximity to water bodies. Figure 25 emphasis this point, as it shows the total number of icing PIREPs within 50 miles of each RAOB location. Figure 26 show the number of PIREPS associated with each location for the three types of aircraft ice. Additionally, icing intensity distribution Figures 27 to 29 draw attention to the fact that with increased intensity, the highest occurrence of icing appears in the Pacific Northwest and around the Great Lakes region. Table 31 shows the total number of icing reports associated with each upper air location and the number of times each type of aircraft icing was reported. Table 32 shows the number of icing reports by intensity of the three types. There were 19 ROAB sites which did not have an icing PIREP meet the criteria for this study. Most of these locations were in Florida or southern California and Texas. The most notable exceptions were Denver CO and Glasgow MT, since the majority of the current icing flight test are being conducted in that region. Figure 30 shows these locations and Table 33 lists them. Lastly, Table 34 shows the location and distribution of the 90 PIREPs removed before the analysis in this study.

TABLE 31, Number of Icing Reports at each RAOB Location

WMO Number	Location Name	Total Reports	Reports by Type Rime	Clear	Mixed
72208	Charleston, SC	5	5	0	0
72210	Tampa, FL	2	1	0	1
72229	Centreville, AL	5	1	1	3
72235	Jackson, MS	6	1	4	1
72240	Lake Charles, LA	4	2	1	1
72247	Longview, TX	2	1	0	1
72260	Stephenville, TX	5	4	0	1
72265	Midland, TX	2	0	2	0
72270	El Paso, TX	2	0	0	2
72274	Tuscon, AZ	1	1	0	0
72293	Mirimar NAS, CA	3	3	0	0
72311	Athens, GA	6	5	1	0
72317	Greensboro, NC	12	7	1	4
72327	Nashville, TN	8	4	3	1
72340	Little Rock, AR	7	5	1	1
72349	Monet, MO	10	1	6	3
72363	Amarillo, TX	8	2	0	6
72387	Desert Rock, NV	3	1	1	1
72402	Wallops Island, VA	7	5	2	0
72403	Washington D.C.	27	15	6	6
72407	Atlantic City, NJ	13	10	1	2
72425	Huntington, WV	15	5	3	7
72429	Dayton, OH	26	11	4	11
72435	Paducah, KY	1	0	0	1
72451	Dodge City, KS	4	0	0	4
72456	Topeka, KS	6	1	1	4
72476	Grand Junction, CO	1	0	1	0
72493	Oakland, CA	4	4	0	0
72518	Albany, NY	46	20	11	15
72520	Pittsburgh, PA	43	25	5	13
72528	Buffalo, NY	53	33	9	11
72532	Peoria, IL	13	3	6	4
72553	North Omaha, NE	17	7	9	1
72562	North Platte, NE	3	0	0	3
72572	Salt Lake City, UT	16	8	2	6
72583	Winnemuca, AZ	4	3	0	1
72597	Medford, OR	10	6	2	2
72606	Portland, OR	11	5	1	5
72637	Flint, MI	32	7	9	16
72645	Green Bay, WI	20	6	8	6

TABLE 31 (CONTINUED)

72654	Huron, SD	6	2	1	3
72655	St Cloud, MN	8	3	1	4
72662	Rapid City, SD	2	0	1	1
72681	Boise, ID	17	14	2	1
72694	Salem, OR	37	14	3	20
72712	Caribou, ME	3	3	0	0
72734	St St Marie, MI	4	0	0	4
72747	International Falls, MN	9	0	7	2
72764	Bismark, ND	26	16	4	6
72775	Great Falls, MT	14	8	4	2
72785	Spokane, WA	32	15	9	8
72797	Quillayute, WA	5	0	3	2
74494	Chatham, MA	5	3	0	2

TABLE 32, Number of Icing Reports by Intensity at Each Location

Location	Rime			Clear			Mixed		
Name	Trace	Light	Mod.	Trace	Light	Mod.	Trace	Light	Mod.
Charleston, SC	4	1	0	0	0	0	0	0	0
Tampa, FL	1	0	0	0	0	0	0	0	1
Centreville, AL	1	0	0	1	0	0	2	1	0
Jackson, MS	1	0	0	0	4	0	1	0	0
Lake Charles, LA	1	1	0	1	0	0	0	1	0
Longview, TX	1	0	0	0	0	0	1	0	0
Stephenville, TX	0	2	2	0	0	0	0	1	0
Midland, TX	0	0	0	2	0	0	0	0	0
El Paso, TX	0	0	0	0	0	0	0	2	0
Tuscon, AZ	1	0	0	0	0	0	0	0	0
Mirimar ANS, CA	1	2	0	0	0	0	0	0	0
Athens, GA	4	1	0	1	0	0	0	0	0
Greensboro, NC	4	2	1	1	0	0	3	1	0
Nashville, TN	4	0	0	1	1	1	0	1	0
Little Rock, AR	4	1	0	0	1	0	0	1	0
Monet, MO	0	0	1	5	1	0	3	0	0
Amarillo,TX	2	0	0	0	0	0	2	0	4
Desert Rock, NV	0	0	1	1	0	0	0	1	0
Wallops Island, VA	2	1	2	2	0	0	0	0	0
Washington D.C.	6	6	3	4	2	0	4	1	1
Atlantic City, NJ	0	8	2	1	0	0	0	2	0
Huntington, WV	1	4	0	1	2	0	1	5	1
Dayton, OH	4	2	5	2	2	0	7	4	0
Paducah, KY	0	0	0	0	0	0	0	0	1
Dodge City, KS	0	0	0	0	0	0	0	1	3
Topeka, KS	0	1	0	0	1	0	0	1	3
Grand Junction, CO	0	0	0	1	0	0	0	0	0
Oakland, CA	1	3	0	0	0	0	0	0	0
Albany, NY	8	10	2	6	4	1	7	7	1
Pittsburgh, PA	7	13	5	1	3	1	4	7	2
Buffalo, NY	13	12	8	2	6	1	6	5	0
Peoria, IL	2	1	0	6	0	0	1	1	2
North Omaha, NE	4	3	0	5	4	0	1	0	0
North Platte, NE	0	0	0	0	0	0	1	2	0
Salt Lake City, UT	2	5	1	2	0	0	5	1	0
Winnemuca, NV	0	1	2	0	0	0	1	0	0
Medford, OR	2	4	0	1	1	0	0	2	0
Portland, OR	1	1	3	1	0	0	2	2	1

Table 32 (Continued)

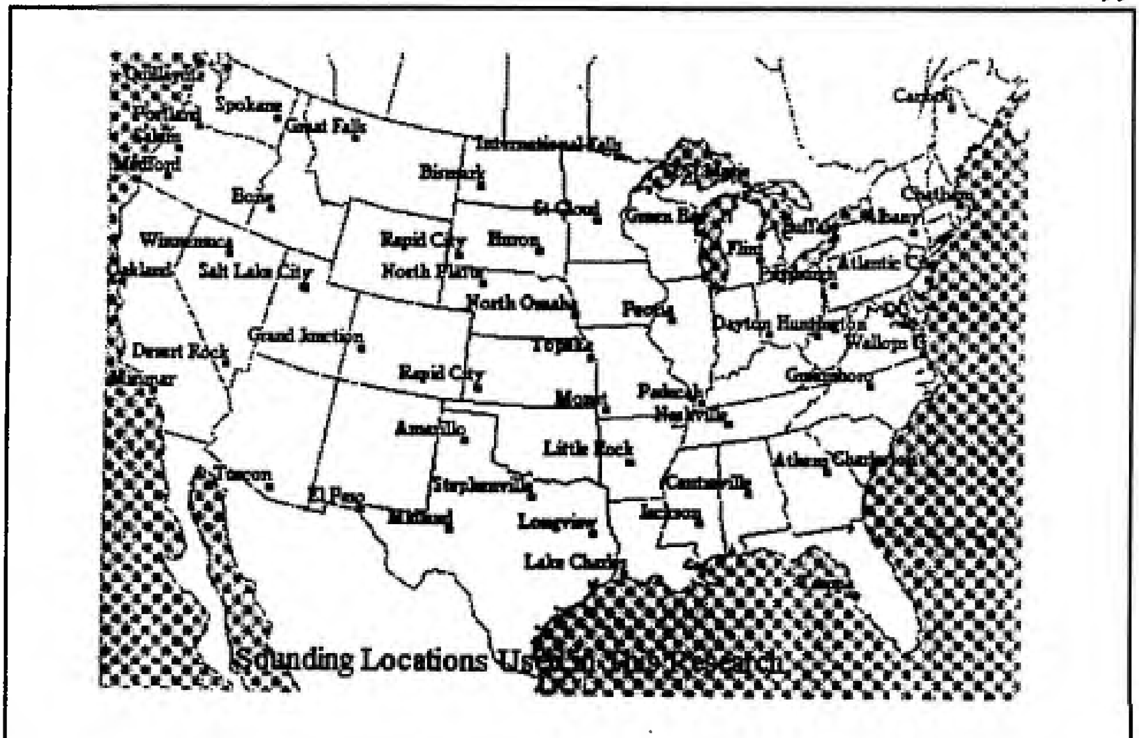
Flint, MI	4	1	2	6	3	0	9	6	1
Green Bay, WI	2	3	1	5	3	0	4	2	0
Huron,SD	2	0	0	1	0	0	0	3	0
St Cloud, MN	0	3	0	0	1	0	0	3	1
Rapid City, SD	0	0	0	0	1	0	0	1	0
Boise, ID	7	6	1	2	0	0	0	1	0
Salem, OR	6	8	0	0	3	0	13	7	0
Caribou, ME	2	1	0	0	0	0	0	0	0
St St Marie, MI	0	0	0	0	0	0	0	4	0
International Falls, MI	0	0	0	0	3	4	0	2	0
Bismark, ND	10	6	0	4	0	0	4	2	0
Great Falls, MT	4	2	2	2	2	0	0	2	0
Spokane, WA	7	4	4	2	7	0	3	4	1
Quillayute, WA	0	0	0	1	2	0	0	2	0
Chatham, MA	2	0	1	0	0	0	0	2	0

TABLE 33, RAOB Locations with no Icing PIREPS in this Study

RAOB Locations with no Icing PIREPS in this Study		
Albuquerque, NM	Brownsville, TX	Cape Hatteras, NC
Del Rio, TX	Denver, CO	Corpus Christi, TX
Edwards AFB, CA	Eglin AFB, FL	Ely, NV
Glasgow, MT	Key West, FL	Norman, OK
Point Mugu, CA	Slidell, LA	Tallahassee, FL
Waycross, GA	Winslow, AZ	Vandenburg AFB, CA
	West Palm Beach, FL	

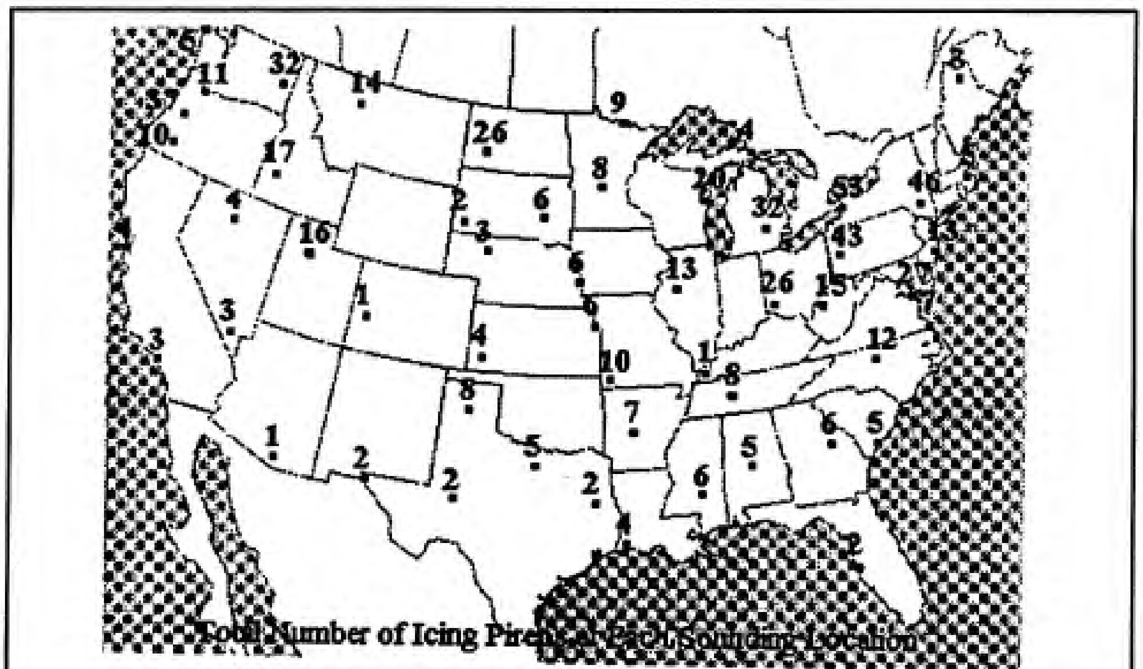
TABLE 34, The number of removed Icing Reports at each RAOB Station

Location Name	Total Removed	Number by Type Rime	Clear	Mixed
Longview, TX	2	2	0	0
Mirimar AFB, CA	2	0	2	0
Nashville, TN	1	0	1	0
Little Rock, AR	2	2	0	0
Monet, MO	5	1	1	3
Atlantic City, NJ	1	1	0	0
Dayton, OH	2	0	0	2
Oakland, CA	5	2	1	2
Albany, NY	1	0	0	1
Pittsburgh, PA	9	3	0	6
Buffalo, NY	8	4	2	2
Peoria, IL	7	0	3	2
North Omaha, NE	2	2	0	0
North Platte, NE	3	2	0	1
Salt Lake City, UT	2	1	0	1
Medford, OR	2	0	0	2
Flint, MI	4	1	1	2
Green Bay, WI	5	3	1	1
Huron, SD	1	0	0	1
St Cloud, MN	2	0	0	2
Salem, OR	6	1	2	3
Caribou, ME	1	1	0	0
International Falls, MN	3	2	0	1
Spokane, WA	7	5	0	2
Chatham, MA	6	4	2	0



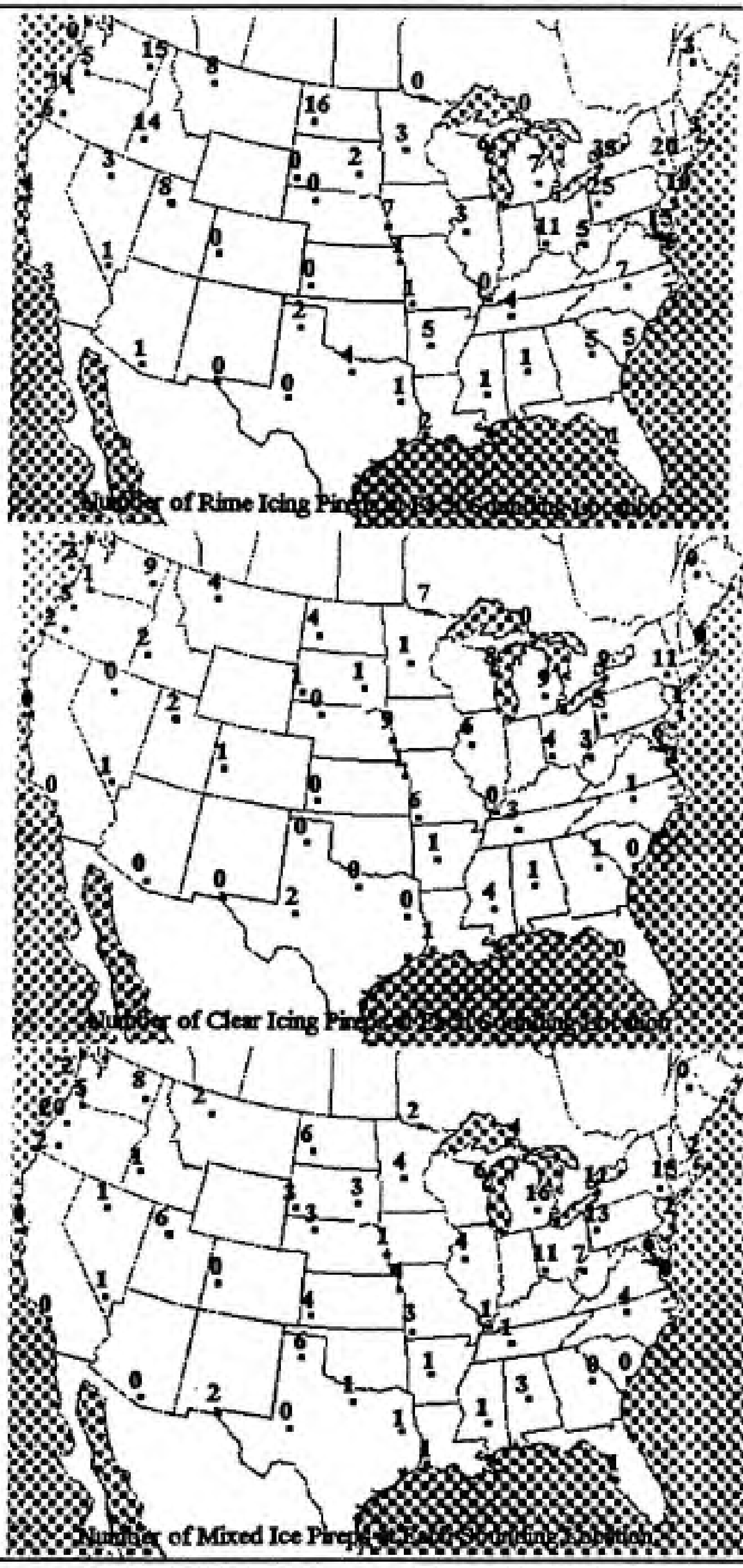
Sounding Locations Used in This Research

FIGURE 24, Sounding Locations Used in This Research



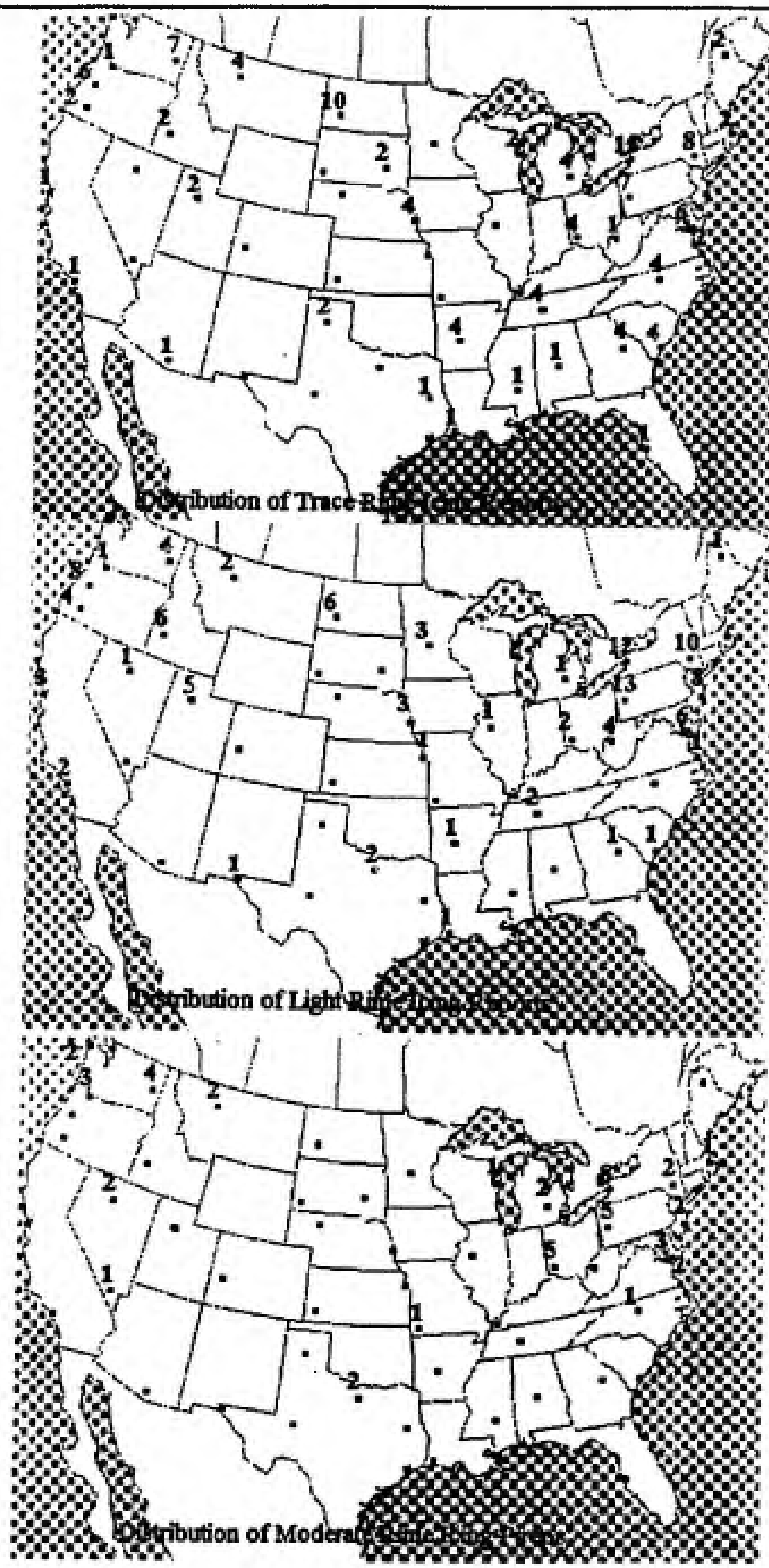
Total Number of Icing PIREPs at Each Sounding Locations

FIGURE 25, Total Number of Icing PIREPs at Each Sounding Locations



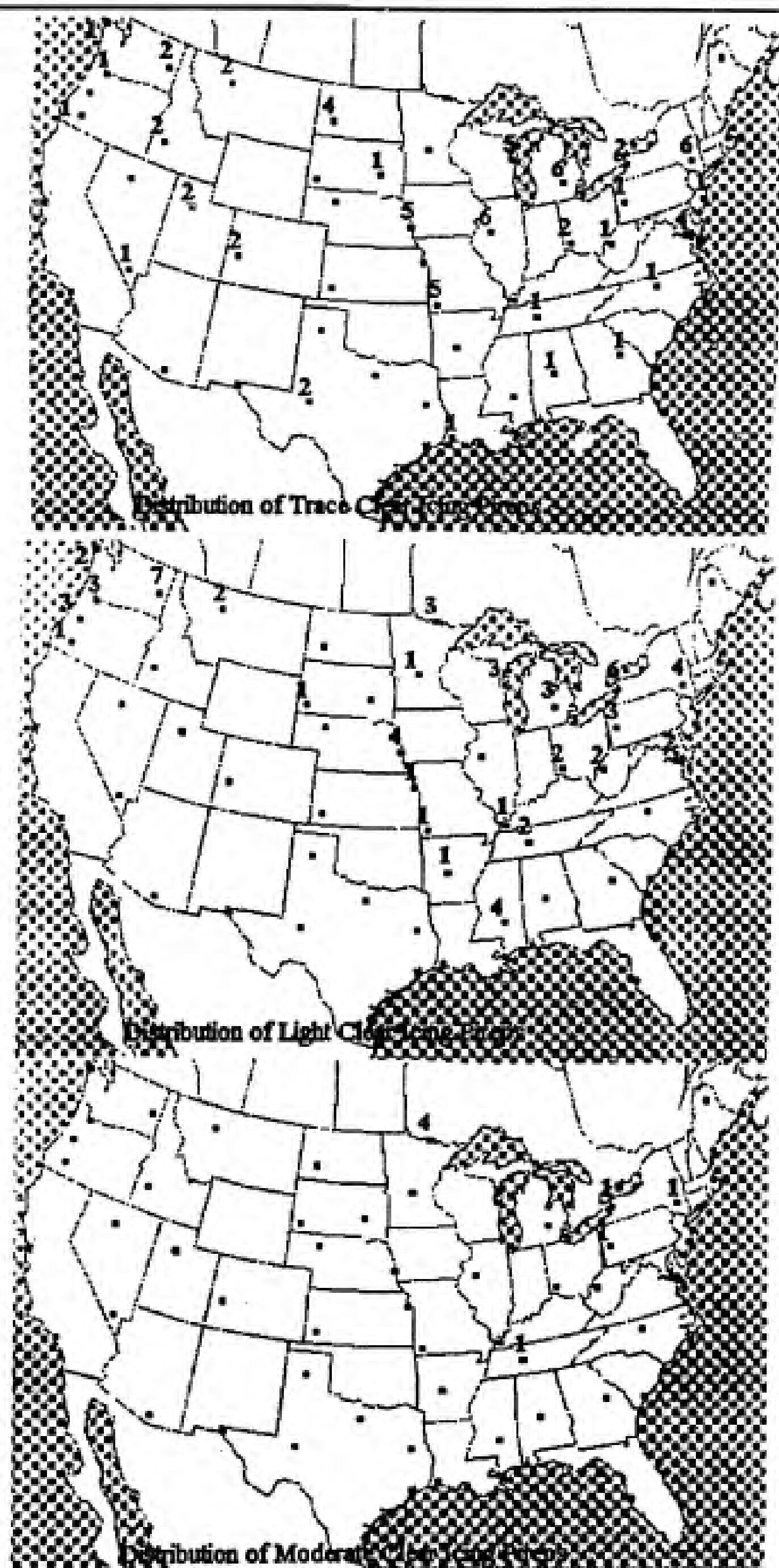
Number of Icing PIREPs by Type at Each Sounding Locations.

FIGURE 26, Number of Icing PIREPs by Type at Each Sounding Locations.



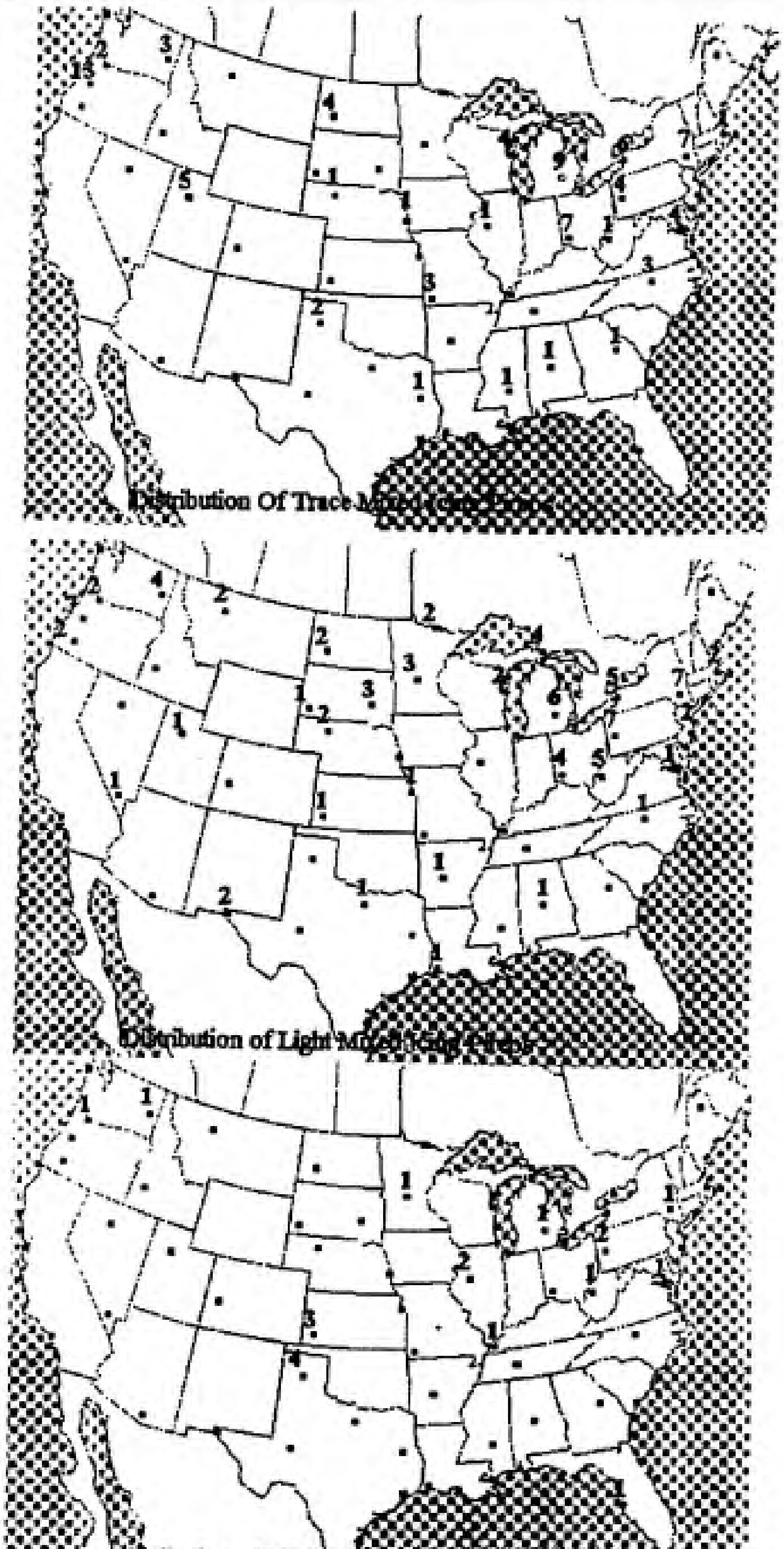
Number of Rime Icing PIREPs by Intensity at Each Sounding Locations.

FIGURE 27, Number of Rime Icing PIREPs by Intensity at Each Sounding Locations.



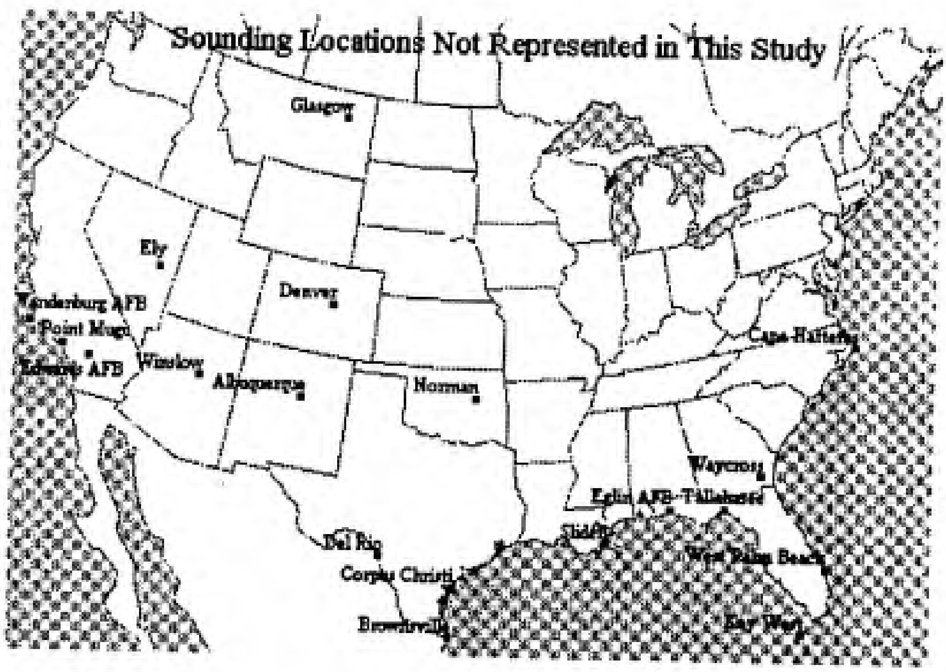
Number of Clear Icing PIREPs by Intensity at Each Sounding Locations.

FIGURE 28, Number of Clear Icing PIREPs by Intensity at Each Sounding Locations.



Number of Mixed Icing PIREPs by Intensity at Each Sounding Locations.

FIGURE 29, Number of Mixed Icing PIREPs by Intensity at Each Location.



Sounding Locations not Represented in this Study

FIGURE 30, Sounding Locations not Represented in this Study

APPENDIX C

ANALYSIS OF THE PIREPS REMOVED DURING THIS STUDY

ANALYSIS OF THE PIREPS REMOVED DURING THIS STUDY

Since over 12 percent of the original data set was removed , this paper summarized the statistics of the removed data and produced this appendix. The monthly distribution of the removed data resembled the original and revised data set distribution (Table 35), with the Spring as the most frequent season followed by Winter. March was the most frequent month for aircraft icing reports in this data set followed by January. There were a higher percentage of icing PIREPs removed from the summer months. December had the highest percentage (18.8 percent) of icing reports removed from the original data set and July was second most effected month (16 percent). The three types of aircraft icing were equally removed (Table 36) except for a slightly higher percentage for the Mixed ice reports. The biggest effect from the removal of these data was on the time of occurrence which is depicted in Table 37. Three quarters of the PIREPs removed were reported in the early evening, at 00z. This confirms the premise that convective scenarios were responsible for the questionable data; i.e. the aircraft was reporting ice accretion while in cloud, where as nearby the sounding ascended through dry air.

Table 35, Distribution of Removed Icing PIREPs by Month

Distribution of Removed Icing PIREPs by Month												
Month	J	F	M	A	M	J	J	A	S	O	N	D
Total	11	07	25	08	55	04	05	00	00	02	07	17
Percent	12	08	28	09	04	04	05	00	00	02	18	19
Rime Cases	04	04	07	05	01	00	05	00	00	01	05	06
Clear Cases	04	02	06	01	02	01	00	00	00	00	00	02
Mixed Cases	03	01	12	02	01	03	00	00	00	01	02	09

TABLE 36, Distribution of Removed Icing PIREPs by Type

Distribution of Removed Icing PIREPs by Type			
Type	Rime	Clear	Mixed
Number of cases	38	18	34
Percentage	42	20	38

TABLE 37, Distribution of Removed Icing PIREPs by Time

Distribution of Removed Icing PIREPs by Time		
Time	00z	12z
Number of cases	68	22
Percentage	76	24
Rime Cases	27	11
Percentage	71	29
Clear Cases	15	03
Percentage	83	17
Mixed Cases	26	08
Percentage	76	24

The analysis of the PIREPs removed from the original data revealed the same type of results as those used in this study and the statistics from those removed PIREPS are in Tables 38 to 42. Temperature analysis showed same trend but with larger differences in the mean observed in Rime and Clear cases. The environmental lapse rate also revealed the same results with little differences from data used in this thesis. The moisture parameters of the removed PIREPs revealed no significant statistics other than to show that these data were from a relatively dry environment

TABLE 38, Removed PIREP Temperature Analysis by Type (°C)

Removed PIREP Temperature Analysis by Type (°C)				
Statistic	Maximum	Minimum	Mean	Deviation
All PIREPs	1.4	-32.4	-10.7	8.99
Rime PIREPs	0.3	-32.4	-14.3	10.1
Clear PIREPs	1.1	-12.7	-5.56	4.60
Mixed PIREPs	1.4	-31.5	-9.33	7.84

TABLE 39, Removed PIREP Relative Humidity Analysis by Type (Percentage)

Removed PIREP Relative Humidity Analysis by Type (Percentage)				
Statistic	Maximum	Minimum	Mean	Deviation
All PIREPs	69.0	3.5	28.15	14.95
Rime PIREPs	56.9	3.5	24.61	14.69
Clear PIREPs	47.4	7.9	30.37	12.46
Mixed PIREPs	69.0	6.6	30.92	16.00

TABLE 40, Removed PIREP Dew Point Temperature Analysis by Type (°C)

Removed PIREP Dew Point Temperature Analysis by Type (°C)				
Statistic	Maximum	Minimum	Mean	Deviation
All PIREPs	-9	-62.4	-28.41	11.0
Rime PIREPs	-9.3	-62.4	-33.02	13.0
Clear PIREPs	-17.1	-35.7	-22.86	5.19
Mixed PIREPs	-9	-41.4	-26.2	8.77

TABLE 41, Removed PIREP Lapse Rate Analysis by Type (°C/1000 Feet)

Removed PIREP Lapse Rate Analysis by Type (°C/1000 Feet)				
Statistic	Maximum	Minimum	Mean	Deviation
All PIREPs	3.2	-3	1.28	1.12
Rime PIREPs	3.2	-0.6	1.38	0.98
Clear PIREPs	2.3	-3	0.87	1.36
Mixed PIREPs	3	-0.7	1.39	1.10

TABLE 42, Removed PIREP Dew Point Spread Analysis by Type (°C)

Removed PIREP Dew Point Spread Analysis by Type (°C)				
Statistic	Maximum	Minimum	Mean	Deviation
All PIREPs	30	9	17.75	7.54
Rime PIREPs	30	9.20	18.75	7.65
Clear PIREPs	30	9.160	17.31	6.64
Mixed PIREPs	30	9	16.87	7.95

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