Understanding In-Flight Icing

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Introduction

In recent years there has been growing concern over the issue of aircraft structural icing. It is the cause of approximately 30 fatalities and 14 injuries, on average, per year as well as US $96 million annually in personal injuries and damages in the United States alone (Hallet et al, 2002). In 1997 the Federal Aviation Administration (FAA) released its In-flight Aircraft Icing Plan which contained explicit recommendations for a comprehensive redefinition of aircraft icing certification envelopes (Cober and Isaac, 2002). This recommendation stemmed from the October 1994 crash of an ATR-72 near Roselawn Indiana, which was attributed primarily to severe structural icing. Since 1994 there have been several more serious accidents involving aircraft icing which have further increased motivation to better our understanding of icing conditions so that they can more accurately be characterized, detected and predicted.

1995 saw the first Canadian Freezing Drizzle Experiment (CFDE) conducted out of St. John's Newfoundland. Subsequent studies in 1996/1997, 1997/1998 and 1999/2000, 2002/2003, 2003/2004 referred to as CFDE II/III and AIRS I/1.5/II, respectively, were conducted out of Ottawa, Ontario with flights over the Montreal, Quebec region during AIRS. All studies employed in-situ measurements using research aircraft like the NRC Convair-580, the NASA-Glenn Twin Otter and the SPEC Lear-25 as well as ground-based remote sensing units such as radar and lidar. The main objectives of AIRS, the most recent study, in order of priority were the following: 1) to improve our ability to remotely sense aircraft icing regions using satellite, aircraft or ground-based systems, 2) to obtain additional data to characterize the icing environment which might be used in a revision of "FAR-25 Appendix C", the criteria used to certify aircraft for icing conditions, 3) to improve our ability to forecast icing conditions and to understand how these conditions develop, and 4) to obtain measurements of aircraft performance within icing conditions and shapes of accretion that might be used on verification of icing model codes or in wind tunnel studies to simulate icing conditions (Isaac et al., 2001). AIRS was the joint effort between many interested parties who contributed both ground and air based measurement equipment as well as funding for the program.

Recent studies have shown that pilot awareness and understanding about in-flight icing needs improvement. Of particular concern are pilots' understanding of conditions that cause *supercooled liquid water* (SLW) to form in the atmosphere, the dynamics of icing and the performance degradation associated with icing encounters. In this paper we will attempt to examine some of these aspects of icing. We will begin with the physics of icing, followed by the dynamics of icing and conclude with flight planning and in-flight strategies. At the end of this paper there are included references which are highly recommended for anyone intending to fly into icing conditions.

Physics of Icing

Before speculating as to where icing conditions are likely to exist along our intended route of flight, we must understand the physics of how *supercooled liquid water* (SLW) is formed in our atmosphere. To do so, we will begin with the basics of cloud droplet formation and work our way up through the various scales that are of interest to us in studying icing. Before continuing however, it will be necessary to go through a bit of the nomenclature that will be used throughout the following discussion.

Some basic definitions

In general, when someone says the word *water* most people think of liquid. What is unique about water however is that it has the ability to exist in our atmosphere, in equilibrium, in all three phases (solid, liquid and vapour). Transition between phases takes place all the time in our atmosphere and results in what we refer to as *weather*. In every transition, energy known as *latent heat*, is either absorbed or released by the water molecules in question. **Figure 1** shows the various phase transitions and their associated names.

- *Condensation* is the process by which water changes phase from vapour to liquid. This process releases energy to its surroundings because liquid is a lower energy state than vapour.
- *Evaporation* is just the opposite of condensation, wherein a phase change from liquid to vapour occurs. This process consumes energy from its surroundings because the system moves to a higher energy state.
- *Freezing* is the process by which water changes phase from liquid to solid (ice). This process, like condensation, releases energy to the atmosphere because ice is a lower energy state than liquid.
- *Melting* is just the opposite of freezing, wherein a phase change from solid to liquid occurs. This process consumes energy from its surroundings because it moves to a higher energy state.
- *Sublimation* is the term used for the transition between solid and vapour in either direction. Transition from vapour to solid is often also called *deposition*, although both terms are correct. In the interest of clarity, we will use sublimation to refer to transitions from solid to vapour and deposition to refer to transitions from vapour to solid. Clearly sublimation consumes energy from the surroundings and deposition releases energy.

To summarize, the three phases in order of increasing energy state are: solid→liquid→vapour. When changing phase from left to right, energy must be *absorbed* by the water molecules from the surroundings. When changing phase from right to left, energy is *released* by the water molecules to the surroundings.

It isn't necessary to memorize **Figure 1**, but there are two points to note about the phase transitions of water that are paramount in our understanding of icing physics. Firstly, liquid water and ice can co-exist in equilibrium at 0 °C. It is the point where phase transition between liquid water and ice should naturally occur. People will often use the terms *melting point* and *freezing point* interchangeably to refer to this temperature, but as will become clear later in our discussion, ice will always begin to melt when temperatures are just slightly above 0 °C, but liquid water will not always solidify when temperatures drop below 0 °C. In essence, this is why we must contend with aircraft icing. The second point is that evaporation, sublimation and deposition need not occur at any specific temperature. In general, there are temperature regimes in which these processes are often more likely, but the reasons for this are beyond our discussion in this paper and will not affect our understanding of aircraft icing.

The formation of clouds and cloud droplets

Clouds are visible moisture in the atmosphere. This moisture can be in the form of liquid water droplets or ice crystals. They can form through any number of processes, but in all cases the air must be cooled to saturation for visible moisture to develop. This cooling will generally be the result of air being lifted and cooled as a result of terrain, fronts, buoyancy, etc. We will discuss this further shortly, but let's digress for a moment to clarify our understanding of water vapour in the atmosphere. Pilot's are generally taught to look at the temperature-dew point spread to determine how close to saturation the air is. In other words, the smaller the temperature-dew point spread the higher the relative humidity. Thus, supposing we lift an air parcel from the surface, with a temperature of 12 °C and a dew point of 10 °C, we would expect condensation (i.e. cloud development) to form about 700 ft AGL. Now suppose we take another parcel of air with a temperature of 20 °C and a dew point of 10 °C and lift it, we would expect to find cloud bases just above 3000 ft. (These estimations are based on the dry adiabatic lapse rate of 3 °C/1000 ft, which provides reasonable results for the lowest few thousand feet of the atmosphere). Clearly the first parcel had a higher relative humidity than the second, but it is also important to note that both parcels have the same *absolute humidity* – the actual amount of water vapour stored in the parcel. Dew point temperature is a measure of water vapour in a parcel (not temperature), and roughly speaking it is a measure of how much water vapour is available for condensation and cloud development. As a rule, dew point is always less than or equal to the temperature. So temperature puts a cap on dew point and hence the amount of water vapour that an air parcel can hold. There are many complications to this problem but in general higher dew points combined with strong lifting can produce clouds of relatively higher liquid water content (LWC).

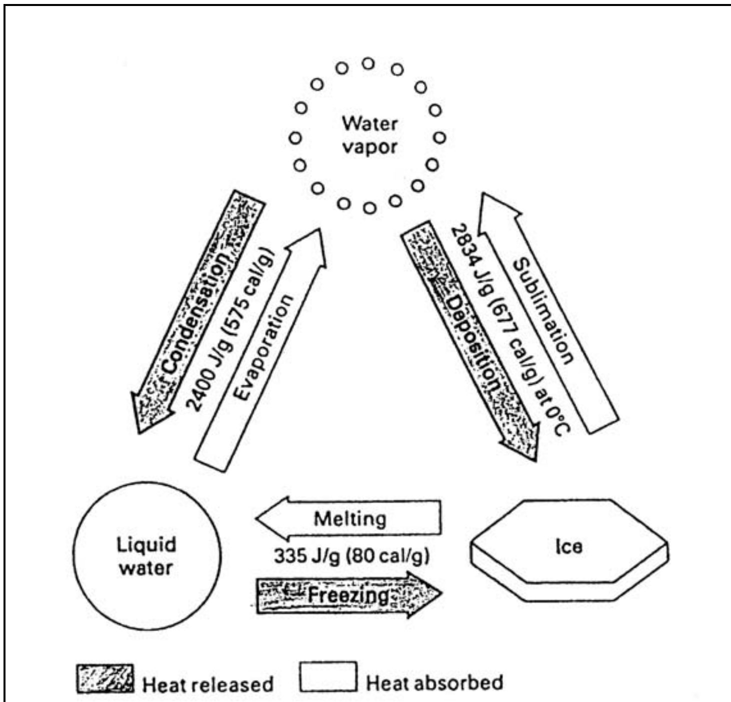

Figure 1 – *Phase transitions of water and associated latent heats*

Consider first the formation of a *warm cloud*. We define this as a cloud with temperatures throughout its depth entirely above 0 °C. In such a cloud we expect to find only liquid cloud droplets. In most cases the cloud forms as a result of some lifting mechanism which brings the air to saturation. This mechanism can be frontal lifting, orographic lifting (air flowing up terrain), buoyancy, convergence, turbulence or any host of other possibilities. As the air is lifted it expands and cools until it reaches saturation (relative humidity, RH = 100 %). Further lifting beyond this point, without the production of visible moisture, would result in supersaturation where RH > 100 %. The level at which saturation occurs is known as the *lifting condensation level* (LCL). Up to this point the amount of moisture contained in the air has remained constant. Beyond this point we observe the *nucleation* (formation) of cloud droplets through the process of condensation, and hence the conversion of some of the water vapour into liquid water. Nucleation comes in two flavours, homogeneous and heterogeneous. Homogeneous nucleation is the direct transformation from vapour to liquid. For reasons beyond our discussion here, this mechanism is not observed in the atmosphere. Rather, the latter mechanism prevails in the atmosphere wherein vapour condenses onto tiny particles called *cloud condensation nuclei* (CCN). These particles can be anything from salts, dust, biogenic and anthropogenic materials, etc., but the important point is that they are <u>always in abundance in the atmosphere</u>. Hence supersaturation in clouds is usually quite limited because once the LCL is reached, vapour is quickly condensed into cloud droplets. Typical cloud droplet diameters range in size from about 10 to 20 microns (1 micron is 10^{-6} metres). Also worth mentioning is that the time scales on which average cumulus clouds are formed is on the order of 10 to 20 minutes.

Once the cloud has formed, if the conditions are right, rain may be produced in as little as 10 minutes. Up to this point the cloud droplets grew by condensation of water vapour onto existing drops. But once they reach about 20 microns in diameter a new process begins to prevail. This process is known as *collision and coalescence*. Simply put, cloud droplets can grow rapidly by colliding with one another and sticking together. As they grow, their fall speeds increase and they scavenge more droplets on the way down. Eventually, the fall speeds of these droplets exceeds the updraft speed of the cloud and we get precipitation. Typically, stratus clouds have much smaller updraft velocities than cumulus clouds (20 to 30 cm/s <u>vs</u> several metres per second), so stratus clouds can often only support drizzle (100 to 500 microns in diameter) whereas cumulus clouds more often produce rain (500 to 5000 microns in diameter). This entire process, from start to finish, is referred to as the *warm rain process*.

Now let's consider how ice particles and snow are formed. The situation begins in the same manner as the warm cloud process except that this time, some or all of the cloud is below 0 °C. Once air is lifted to the 0 °C isotherm (freezing level) and visible moisture is present, there is a possibility of forming ice particles. This can occur through the freezing of liquid droplets or by direct deposition (vapour to ice). Like the warm cloud process, ice particles must also form on some sort of nucleus, but in this case they are called *ice* or *freezing nuclei* (IN/FN). All things being equal, snow and ice particles would develop as soon as saturated air reached the freezing level, but as we find in the atmosphere FN are far less abundant than CCN. Thus even though liquid droplets may be lifted well above the freezing level, they are not guaranteed to freeze unless they come into contact with a FN. Liquid droplets that exist below 0 °C are referred to as *supercooled droplets*. To put things into perspective, at 0 °C only about one FN in every one million CCN is found to exist (pretty poor odds!). The number concentration of FN has been found to correlate well with temperature, as shown in **Figure 2**, and moreover we see that only negligible concentrations of FN exist at temperatures above –15 °C. This is one reason why observations have shown that in general, aircraft icing conditions are most hazardous and most common when cloud temperatures are warmer than about –15 °C (remember though, this is *in general*, it is not a rule!). It should also be noted that once ice particles begin to form, they can quickly multiply and deplete the liquid water in a cloud. This process is known as *glaciation*. This is why meteorologists are often concerned with cloud top temperatures (CCT). If the CCT is below –15 °C there is a greater likelihood of ice particles forming near the top of the cloud and glaciating the cloud from the top down. However, even this rationale can break down if the updraft velocities in the cloud are strong enough. Zawadzki, et al (2000) showed the conditions under which liquid water and ice can co-exist in a cloud. That being said, the main point to remember is that when temperatures are between 0 °C and –40 °C there is always the possibility of SLW existing in cloud, it is just that the probability of finding SLW begins to decrease as temperatures drop below –15 °C. –40 °C is given as the lower limit because this is the theoretical temperature at which SLW freezes spontaneously.

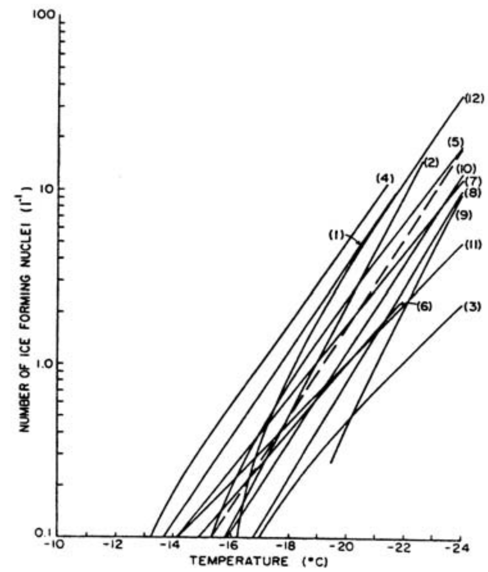

Figure 2 – *Concentrations of Freezing Nuclei as a function of temperature. Lines represent results from various researchers. (Pruppacher and Klett,1997)*

Let's summarize briefly the important points to remember about cloud microphysics. First, latent heat is absorbed or released during the various phase transitions of water. The relevance of this to in-flight icing will become apparent in subsequent sections. Second, dew point is a measure of the absolute humidity of the air, not temperature. So when assessing the available moisture in an airmass, remember that although temperature will put a cap on the dew point, it is dew point that actually reveals the moisture content of the air. Also, strong and/or sustained updrafts can often yield relatively high LWC values and large droplet environments (provided the moisture is available for condensation). Upslope flow around mountains and fronts can be the ideal locations for these conditions to form. With respect to warm clouds, droplets are formed though condensation onto CCN, followed by growth to precipitation through the collision-coalescence process. In cold clouds, ice particles can form either by direct deposition onto FN or by the freezing of existing droplets when they come into contact with an FN. However, given the relative scarcity of FN, it is not unlikely to find liquid droplets at temperatures well below 0 °C. These liquid droplets may form in above freezing temperatures and then get lifted up above the freezing level, or they may form entirely below 0 °C. Recall that CCN are very abundant in the atmosphere, so when the LCL is reached, if no FN are available supercooled liquid will naturally condense onto CCN. For completeness, I should also mention that rain can be produced by snowflakes that form in sub-freezing temperatures aloft, and then fall below the freezing level were they melt and hit the ground as rain. This however doesn't really affect our discussion on aircraft icing.

From cloud droplets to precipitation

We have already mentioned the process by which warm rain forms. We now consider how several other types of precipitation form and how they affect aircraft icing conditions. We will also examine how these precipitation types are observed at the ground in the hopes that it may help us infer what icing conditions are likely to exist aloft. (NOTE: The information in this section is derived primarily from the COMET training module entitled "Icing Assessment Using Observations and Pilot Reports"). The following discussion will focus on snow (SN), graupel/snow pellets (GS), freezing drizzle (FZDZ), freezing rain (FZRA) and ice pellets (PL).

When snow conditions exist at the ground, the likelihood of icing aloft is reduced. Recall firstly that when clouds contain ice particles they tend to glaciate relatively quickly. So a cloud which is producing precipitation sized snow particles is less likely to contain SLW. If you have the benefit of being at the site where snow has fallen, take a closer look at the particles that hit the ground. If the snowflakes are pristine, you can be more confident that the lowest cloud layer has little or no SLW. If on the other hand you observe tiny droplets frozen to the snowflake you will probably encounter some SLW while in cloud. This is evidenced by the small frozen droplets that were collected by the snowflake as it fell through the cloud. In any event, snowflakes at the ground reduce the likelihood of finding SLW in the lowest cloud layer, but it by no means eliminates the possibility! Remember, liquid water and ice can co-exist and many studies have shown this. As well, snow falling at the surface does not say anything about upper cloud layers.

Graupel or snow pellets, occur at the ground when snowflakes fall into a region containing high SLW. The snowflake becomes so heavily rimed with SLW that its original structure is collapsed and completely unrecognizable. Graupel at the surface is certainly an indicator that significant amounts of SLW are likely to exist aloft. Large graupel can also be an indicator of the presence of thunderstorms. Use caution when flying through regions where graupel is reported at the surface.

Freezing rain can form through two methods. In the first, ice-phase precipitation falls into an above-freezing layer aloft (inversion), melts or partially melts and then supercools as it falls into a sub-freezing layer below. This is referred to as the *classical mechanism* for freezing rain formation. This situation is often associated with frontal inversions, but can result from many other processes as well. One example is when sub-freezing air is channelled into a valley below a layer of above-freezing air. Even though stations in the surrounding area may be reporting only rain, areas within the valley may experience freezing rain. The second mechanism for freezing rain formation is dubbed the *non-classical mechanism*. Here, SLW forms entirely through collision and coalescence, otherwise known as the *warm rain process*. In this case no melting layer exists aloft. This is important to note, because pilots should not expect that a climb will take them into an above freezing layer. In one study by Huffman and Norman (1988), they showed that about 62 % of freezing rain cases formed through the classical mechanism, while 38 % were attributed to the non-classical mechanism. When freezing rain is reported, expect that significant icing conditions exist from the surface to some level above ground. Also be cautious that even if a melting layer does exist, there may still be SLW above the layer that has formed through the collision-coalescence process.

There is no clear division between freezing drizzle and freezing rain, but for our purposes we will define freezing drizzle as supercooled precipitation-sized particles with a diameter less than 500 microns. Freezing rain is thus defined as having a diameter of greater than 500 microns. Freezing drizzle more often forms through the non-classical mechanism but has been shown to form through the classical mechanism as well. Huffman and Norman (1988) found that 78 % of the cases they studied were formed through the non-classical mechanism, while about 22 % formed through the classical mechanism. Freezing drizzle, like freezing rain, is a good indicator that significant icing conditions exist from the surface to some level above ground.

Ice pellets form through a manner similar to the classical mechanism, only in this case the melting layer is usually shallower. Snow falling into the layer partially melts and then refreezes as it falls into the sub-freezing layer below. The presence of ice pellets at the surface suggests that freezing rain or freezing drizzle exists at some altitude above ground, and hence significant icing conditions can be expected. I must reiterate that both the classical and non-classical mechanisms can be present at the same time; thus icing conditions may exist well above the melting layer.

Observed properties of clouds

The majority of aircraft icing encounters will take place in cloud. As a result, it is worth while taking a moment to examine some of the observed properties of clouds so that we can more safely navigate this beautiful, but sometimes deadly phenomenon.

Cumuliform clouds are less likely in the winter than in the summer, but have been observed at all times of the year. Typically the droplet concentrations ($\#/m^3$) are higher and liquid water contents (LWC) lie between 0.1 to 3.0 g/m^3 (Paraschivoiu and Saeed). Droplets also tend to be skewed toward larger diameters as updraft velocities are typically several metres per second. These clouds tend to produce greater rates of ice accretion, but their horizontal extents are usually on the order of 5 to 10 km. The lifecycle of an average cumulus is about 30 min, but cumulus that are associated with large scale systems like fronts and cyclones can continually regenerate resulting in a quasi-steady state that can last for days. Cumulus, and in particular cumulonimbus, should be considered to have high LWC and large drops and should be avoided whenever possible. Icing conditions in these clouds can extend many thousands of feet vertically and even short exposure times can prove to be hazardous.

Stratiform clouds are far more common in the winter than cumuliform. Although these clouds are generally perceived as being less of a threat, many icing accidents have occurred in these clouds. LWC tends to range between 0.1 and 0.8 g/m^3 (Paraschivoiu and Saeed), but higher values have been observed. Droplet sizes are usually smaller than in cumulus although this is not a guarantee. Stratiform clouds tend to be more limited in vertical extent than cumulus, but can span many hundreds of kilometres horizontally. Many freezing precipitation events originate from stratiform clouds, often through the collision-coalescence process, and given their large horizontal range can leave an unsuspecting pilot without any outs. The best option is usually to fly above the cloud layer, but be careful on the climb-out because the *highest LWC and the largest droplets are often found at or near the cloud top*. Incidentally, this can also be true for cumuliform clouds as well, depending on where the tops are.

Perkins and Reike (2001) report on some statistical findings of aircraft icing environments. Results of some of these findings are shown in **Figures 3**. For stratiform and cumuliform clouds, 90 % have LWC less than 0.6 g/m^3 and 1.2 g/m^3, respectively. Also, 90 % of layered clouds have vertical extents of 3000 ft or less (**Figure 3a**). In terms of horizontal extent, it has been found that 90 % of icing conditions last 50 statute miles or less (**Figure 3b**). The overall probability of encountering icing along your route of flight is about 40 % when temperatures are at or below 0 °C, and only about 14 % when temperatures drop below –20 °C. Nevertheless, icing conditions do exist at all temperatures down to –40 °C, so caution and preparation are always necessary no matter what the temperature. To put things into perspective, Korolev, *et al* (2002) report on an icing encounter during AIRS in which the NRC Convair-580 encountered severe icing at 18 000 ft and –29 °C. The

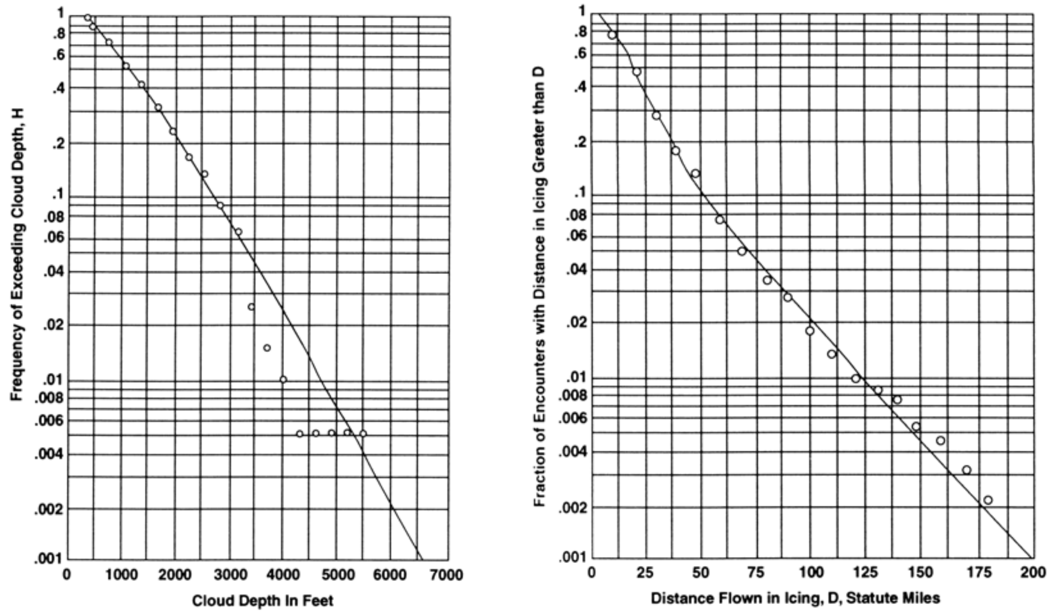

***Figure 3 –** Cumulative frequency distribution of (a) depth of an icing encounter, and (b) distance flown horizontally in icing during an encounter. (From Perkins and Reike, 2001)*

pilots increased power by 20 to 30 % to maintain flight conditions, and after only 5 min were forced to climb above cloud top to deice. The moral, *expect the unexpected!*

Icing Certification and Supercooled Large Droplets (SLD)

The icing environments required for certifying aircraft into icing conditions are outlined in the U.S. Federal Aviation Regulations 23/25 Appendix C for commuter and transport category aircraft, respectively. In Canada, these standards are located in Canadian Aviation Regulations 523/525 Appendix C, again for commuter and transport category aircraft. Although the names are different, the icing environments required under all these regulations are identical. Thus for our purposes, from this point forward we will refer to all of these standards collectively as CAR 525-C.

In order for an aircraft to be certified into *known icing*, the manufacturer must demonstrate that the aircraft can safely penetrate regions with meteorological conditions specified under CAR 525-C. The conditions are shown in **Figures 4 a & b. Figure 4a** is meant to represent icing in layered, or stratiform clouds. This is referred to as *continuous maximum icing*. **Figure 4b** is referred to as *intermittent maximum icing*, and is designed to represent conditions in cumuliform clouds. The curves were developed over 40 years ago by the U.S. National Advisory Committee for Aeronautics (NACA) following flight research. "These design standards were determined on the basis of an ice protection system providing nearly complete protection in 99 percent of the icing encounters, and that some degradation of aircraft performance would be allowed" (Aircraft Icing Handbook, 2000).

There are several important points to note about aircraft icing protection systems. All systems, no matter what category of aircraft, must meet these basic minimums. Some aircraft may be capable of penetrating regions of much greater icing, but these results are not required to be reported during flight testing. So no matter how big or small the aircraft you fly is, don't assume that it is capable of more than the minimums. Furthermore, often pilots believe that aircraft are certified to *remain* in

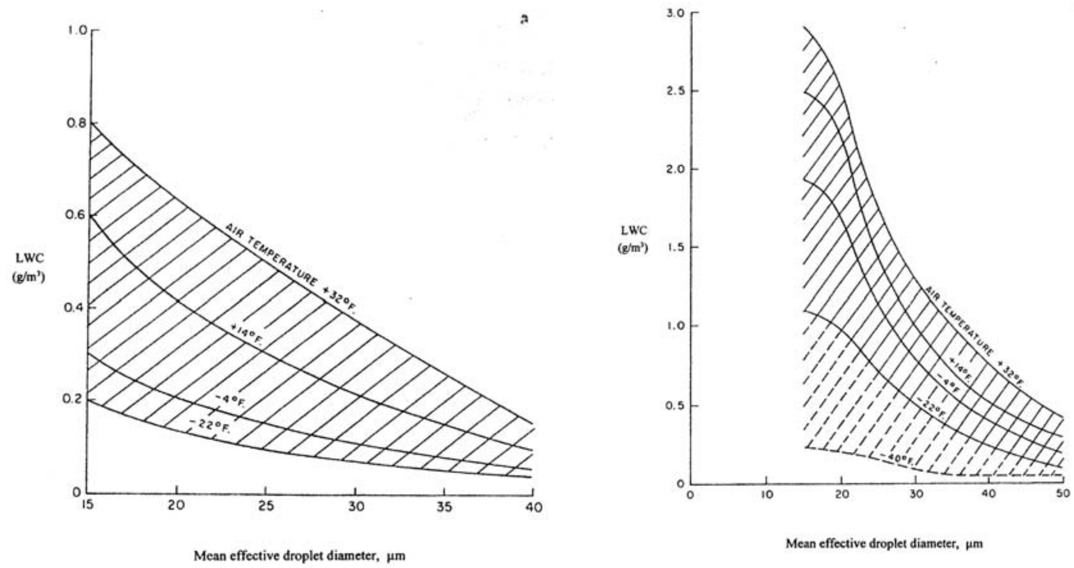

Figure 4 – *CAR 525-C curves for (a) continuous and (b) intermittent maximum icing*

icing conditions. Understand that the CAR 525-C curves are based on standard horizontal extents of 17.4 nautical miles and 2.6 nautical miles for continuous and intermittent maximum icing, respectively. Although flight test standards are quite stringent (such as safely demonstrating a 45 minute hold in icing), aircraft are not designed to remain in icing conditions indefinitely. Should you decide to study icing further, a common theme among all instructional material is the following: *whenever you encounter icing, you should always start working to get out.* We will discuss strategies for this in subsequent sections.

CAR 525-C specifies conditions of LWC, temperature and mean effective drop diameter (MVD) that an aircraft must be able to penetrate. Notice that the curves allow for lower LWC as temperature decreases. Also notice that while intermittent maximum icing allows for MVD up to 50 microns, continuous maximum icing only allows for droplets up to 40 microns. Given that typical droplet radii in cloud are in the range of 10 to 20 microns, this is usually not a concern. However, under certain circumstances these maximum allowable MVDs can be exceeded, and in such cases these droplets are referred to as *supercooled large droplets* (SLD). These insidious creatures are thought to have caused several major icing accidents (including the one in Roselawn Indiana), and have been the focus of much of our present research.

Freezing precipitation is one form of SLD. Freezing drizzle and freezing rain both far exceed the icing certification envelopes and thus should never be intentionally penetrated. But SLD need not be associated with precipitation. In some instances cloud droplets, particularly in clouds of greater vertical extent, can grow by collision-coalescence to sizes much greater than 50 microns. When updraft velocities in cloud are strong enough these droplets can remain in cloud without precipitating out. Also note, that once precipitation leaves the cloud base it enters a sub-saturated region and will begin to evaporate. From this we can infer two things: (1) freezing precipitation is generally most hazardous at cloud base, and (2) freezing precipitation may exist aloft, even if it is not reported at the ground. In the next section we will examine the dynamics of icing and why it is never advisable to fly through regions that exceed CAR 525-C.

The Dynamics of Icing and Icing Intensity Classification

We have already shown that CAR 525-C sets explicit limitations on the LWC, temperature and MVD for aircraft icing environments. In this section we will see how each of these parameters affects flight performance individually and cumulatively. We will begin with the types of icing possible and then describe how the various environmental parameters affect how icing forms on an aircraft and the performance penalties incurred. We will conclude with the standards for classifying icing intensity.

Types of icing

Ice can form on an aircraft anytime liquid water strikes a surface where the total air temperature (TAT) is below freezing. Recall that SLW is a meta-stable state, meaning it only exists because there are insufficient freezing nuclei available for glaciation. The TAT is the sum of the static air temperature (SAT, read off a stationary thermometer) and the kinetic rise resulting from airspeed (Perkins and Reike, 2001). It is necessary to note that the relevant parameter here is TAT, because this value can vary across an airfoil due to pressure variations. For example, the TAT will be highest at the stagnation point on the leading edge of an airfoil because of the local pressure rise. Conversely, the temperature will generally be lowest on the low pressure side of the airfoil (for wings this is the top), as a result of the pressure decrease due to the Bernoulli effect. Wind tunnel testing of a standard airfoil at 150 kts true airspeed, showed a temperature drop of 1.9 °C across the wing (Aircraft Icing Handbook, 2000). Although outside air temperature (OAT) gauges generally measure TAT, never assume that temperature is being reported with complete accuracy and realize also that temperature can vary along an airfoil. Use caution when temperatures are at or slightly above 0 °C.

There are effectively three types of icing that an aircraft can experience: *Clear* (also known as G*laze*), *Rime* and *Mixed*. Clear ice usually occurs in regions where temperatures are near 0 °C and droplets are relatively large. As a result, SLW striking the aircraft does not freeze instantly on impact. As the droplet strikes the wings for example, it partially freezes and releases some latent heat (recall that ice is a lower energy state than liquid, so energy must be released). This latent heat, in combination with the kinetic temperature rise at the leading edge of the airfoil can cause some of the droplets to runback before freezing entirely. This creates a smooth, dense coating of ice that can not only prove to be very hazardous but can also be very difficult to detect visually, especially at night. In addition, if allowed to accumulate it can form protrusions from the leading edge of the airfoil which can significantly reduce aircraft performance. Clear ice is generally perceived as being the most detrimental to flight characteristics (but again, this is not a *rule!*).

Rime ice forms when droplets impacting the airfoil freeze on contact. The conditions most conducive to this type of ice are small droplets and low temperatures. These factors can act to reduce TAT and runback. Because droplets freeze on impact air becomes trapped between the frozen droplets producing a milky white appearance that is much easier to detect than clear ice. Rime tends to be less dense and generally conforms to the airfoil leading edge. It is often seen as being less dangerous than clear icing, but if left unattended can degrade airfoil performance significantly.

The mixed icing category encompasses a continuum of icing types between rime and clear. It can form protrusions like clear ice, but by definition is milky white in colour similar to rime. Mixed icing can degrade performance in the same manner as rime and clear, and should be treated with the same level of caution. **Figure 5** shows a few icing shapes that were produced on a cylinder in the NASA icing wind tunnel, and illustrates the wide range of icing that can be observed in flight.

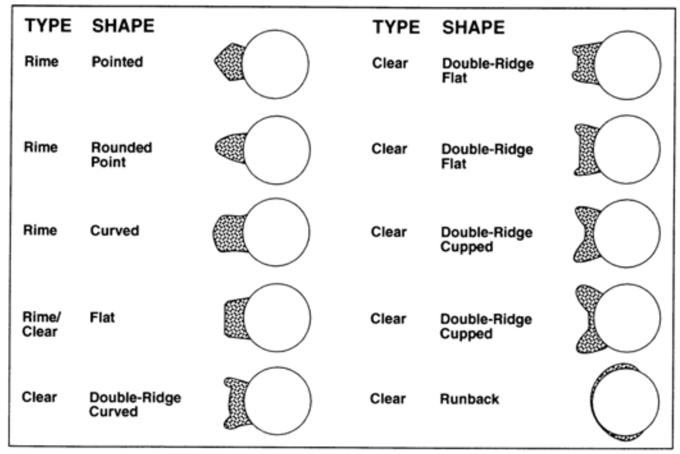

***Figure 5** – A few ice shapes observed on a cylinder in the NASA icing wind tunnel. (From Perkins and Reike, 2001)*

In general, temperature and MVD account for icing type and shape, while LWC and to a lesser degree MVD are responsible for the rate of accretion and hence severity of an icing encounter. It should be noted however that the complex interplay between these three parameters is still not very well understood. LWC is seen as being the most important factor, and it has been speculated that for a given airspeed, temperature and MVD, an increase in LWC may cause a transition from rime ice to clear ice (Hansmann, 1989). Also of supreme importance is the duration of exposure. Longer exposure times will result in more quantities of ice being collected. As well, ice protrusions formed on the leading edge of an airfoil can enhance the collection efficiency of the airfoil and thus ice accretion will not necessarily increase in a linear fashion.

When flight planning, a rule of thumb for determining what type of icing can be expected in cloud is the following: Clear (0°C to –10 °C), Mixed (–10 °C to –15 °C) and Rime (–15 °C to –40 °C). Also, stratiform clouds more typically contain rime while cumuliform are more often associated with clear. These however are very general rules and should only be used as a guideline. Recall also that freezing precipitation, which generally forms clear ice, can be produced in both cumuliform and stratiform clouds at any temperature.

Dynamics of icing

The first point to note about ice accretion is that it is heavily dependent on the shape of the object upon which the droplet is impinging – remember this throughout our discussion. What follows is a general discussion of the dynamics of ice accretion, but it by no means is exhaustive. There are many factors which affect ice accretion and this is still a very active area of research. For more detailed discussion about types of ice protection available, please see the references at the end of this paper.

Ice protection systems on aircraft are designed to meet the conditions specified in CAR 525-C. A closer look at the wing of an aircraft certified for flight into known icing will reveal that on most aircraft, only the leading edge of the wing is protected. This is based on the principle that droplets which fall within the limits of CAR 525-C will not impinge beyond this protected surface. Very small droplets have little inertia and thus for the most part are steered by the airflow. **Figure 6** shows the airflow around a typical airfoil and demonstrates some possible droplet trajectories as a

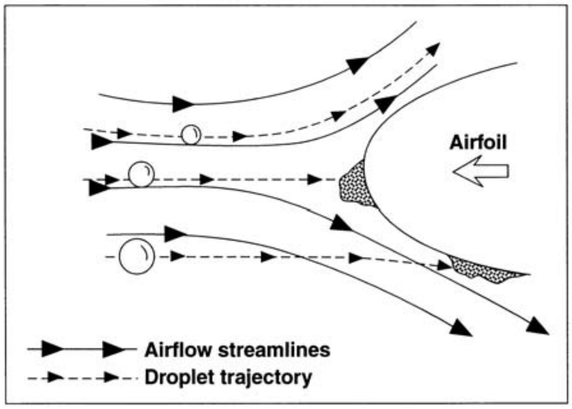

Figure 6 – *Airflow around a typical airfoil. Also shown are possible droplet trajectories. (From Perkins and Reike, 2001)*

Figure 7 – *Picture of icing runback beyond the protected surface (circled). Icing encounter occurred on February 16, 2000 during AIRS and was classified by the pilots as severe. (From Isaac et al, 2001)*

function of droplet size. Notice that small drops either impinge at or near the stagnation point, or are completely deflected around the airfoil by the streamlines. Larger droplets have the ability to break some of the streamlines and impact further aft on the airfoil. As a result, the overall collection efficiency is increased. So even when LWC is low but droplet sizes are large, icing can still be significant. When SLD conditions are encountered, depending on the airfoil, droplets may have the ability to impinge beyond the protected surface. This can produce a ridge of ice beyond the protected surface that cannot be cleared by the ice protection equipment. It can also act as a dam which will rapidly collect ice and grow, causing a further degradation to airfoil performance. *Ridging* is a very dangerous phenomenon and is common of SLD encounters. The best method for removing a ridge of ice is to fly into above-freezing air or to get on top of the cloud where the ice can sublimate. Note that ice-impingement can occur on both sides of the wings when SLD are present. An example of ridging is shown in **Figure 7**.

Ice impingement is also a function of object shape and airspeed. A thicker wing section will tend to deflect streamlines further up stream, and resultantly will generally accrete ice at a slower rate for a given airspeed, temperature, LWC and MVD. As will be discussed near the end of this paper, this is one reason why tailplane horizontal stabilizers have a higher collection efficiency and tend to accrete ice more rapidly than wing sections. Airspeed affects ice accrete in an opposite manner to object size. Higher airspeeds leave less time for the droplets to deflect and hence higher rates of accretion may be observed on faster wing sections. Note however that the TAT when the airspeed is increased will increase proportionally near the leading edge and may in fact bring the wing section above 0 °C (Don't count on this though!). An example of this kinetic heating effect is illustrated by the ice protection equipment on most propeller systems. Often these propellers are heated electro-thermally from the root to about the mid-point along the span in order to prevent or remove ice accretion. From the mid-point to the tip, the propeller is moving fast enough that kinetic heating keeps the blade above 0 °C and does not allow droplets to freeze on this portion of the propeller.

As stated earlier, LWC is perceived as being the most important factor in aircraft icing. As LWC increases the rate of accretion and severity of the icing encounter will increase proportionally. As this happens, increasing amounts of latent heat are released as droplets strike the airfoil and begin to freeze. If enough liquid water is present some of the water may remain in liquid form long enough to runback beyond the protected surface and form a ridge as shown in **Figure 7**. *Runback ice* can be a concern for both pneumatic boots and heated leading edges. In the case of heated leading edges, it is possible under certain circumstances for the thermal device to enhance runback. Under normal operating conditions, thermal de-icing/anti-icing is designed to evaporate most or all of the ice impinging on the protected surface. If the heat supply becomes insufficient to evaporate the water (e.g. due to low power settings, cold temperatures and LWC outside CAR 525-C), SLW impinging on the heated surface may be warmed enough to remain in liquid form and runback beyond the protected surface causing ridging. This is why LWC outside the CAR 525-C curves can be very dangerous.

Performance penalties resulting from ice accretion

The aerodynamic penalties incurred when ice is accreted are given in Paraschivoiu & Saeed and can be summarized as follows:

- Decreased Lift
- Increased drag
- Decreased stall angle
- Increased vibration
- Changes in pressure distribution
- Early boundary layer separation
- Reduced controllability

Icing studies have shown that airfoil drag can increase up to 40 % or more while lift can be reduced by as much as 30 % or more. Even small amounts of ice can increase stall speed by as much as 15 to 20 %. Vibrations can also create added stress on iced components leading to structural damage. Propellers that become heavily iced may experience increased vibrations in addition to a loss of efficiency of up to 19 %. Even when de-icing/anti-icing equipment is properly functioning, residual ice remaining on unprotected surfaces can still be hazardous. On one research mission, the NASA-Glenn Twin Otter experienced a 36 % drag increase resulting from ice collected on the unprotected surfaces. This reiterates the point made earlier, *whenever you encounter icing, you should always start working to get out*.

When icing is encountered be aware that any accreted ice will reduce your stall margin. If you are unable to maintain airspeed and altitude, be prepared to accept a controlled descent in stead of a control anomaly. Your chances of survival are much greater in a controlled descent than in a recovery from a stall or spin.

Classification of aircraft icing environments

Standards for the classification of icing intensities are given in AIP 2.4 and are summarized below.

Trace	*Ice becomes perceptible. The rate of accretion is slightly greater than the rate of sublimation. It is not hazardous, even though de-icing or anti-icing equipment is not used, unless encountered for an extended period of time (over 1 hour)*
Light	*Rate of accumulation may create a problem if flight is prolonged in this environment (over 1 hour)*
Moderate	*The rate of accumulation is such that even short encounters become potentially hazardous, and use of de-icing or anti-icing equipment or diversion is necessary*
Severe	*The rate of accumulation is such that de-icing or anti-icing equipment fails to reduce or control the hazard. Immediate diversion is necessary*

These definitions have been under review for quite some time now. There is much debate as to their usefulness because they can be very subjective. As discussed earlier, different airfoils will accrete ice at different rates. So all things being equal, two aircraft transiting the same region may report two different intensities, based on the fact that one airfoil tends to accrete ice faster than the other. And in reality, all things are not equal, so pilot experience and comfort level will also influence his/her perception of icing intensity. These varying opinions can even be seen between flight crews on research aircraft! So when encountering icing, try to be as objective as possible, but realize that one pilot's light encounter may be another pilot's severe encounter.

Flight Planning

Proper flight planning and preparation are the key to effectively negotiating in-flight icing. Don't be fooled, no matter what aircraft you fly icing is always a hazard, but the risks can be limited by making sure you have done everything possible to secure the safety of your flight. References made to websites in the following paragraphs are also given with full web addresses at the end of this paper.

Checking the weather

We start with a climatology of freezing rain and freezing drizzle over North America as shown by Cortinas, *et* al (2004) in **Figure 8**. From this figure we see that there are in general three distinct maxima; one located over the Great Lakes, one on the southwest side of Hudson Bay and the other across eastern Labrador and Newfoundland. There is also a non-negligible frequency of freezing precipitation which occurs across a large portion of Canada and the central United States. We will not speculate as to why this distribution occurs, but you are encouraged to study this figure to get an insight as to where icing conditions are likely to be. Remember though, this is a climatology based on surface observations; in-flight icing can occur anywhere and at present a concrete climatology of in-flight icing does not exist. In terms of locations of aircraft icing accidents, Cole and Sand (1991) conducted a statistical study of aircraft icing accidents and found that 53 % occurred near mountainous terrain, 14 % occurred near large bodies of water and 33 % occur in other regions. Keep this information in mind when flight planning.

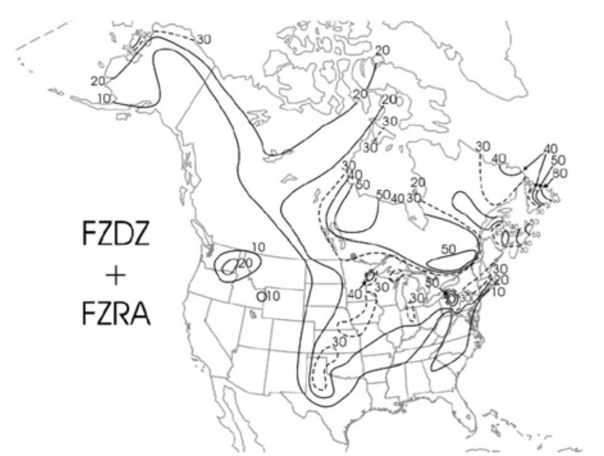

Figure 8 *– Median annual hours of freezing drizzle and freezing rain between 1976 and 1990. (From Cortinas, et al. 2004)*

There is really no correct way to check the weather, but whatever method you use make sure it is systematic. This way you can be sure that you have obtained all the key components to the weather picture. Generally a look at the *big* picture is usually the first step. This can be done by looking at the latest surface analysis given on Environment Canada's weather page (EC), the U.S. Aviation Weather Center (AWC), Aviation Digital Data Service (ADDS) or Nav Canada's flight planning site (NC). NC is the usual reference for Canadian pilots, but I encourage you to check out some of the other weather links. In particular, if you're flying down to the U.S., ADDS has a lot of great weather resources available to pilots. Based on your knowledge of icing physics, you can begin to draw a mental picture of where icing conditions may exist. Although icing is always a possibility when TAT is at or below 0 °C, you can improve your analysis by identifying regions conducive to the formation of high LWC and large droplet environments. Look for regions of strong and/or persistent lifting such as fronts, low pressure centers (cyclones) and areas of upslope flow. The latter point is an important one. When forecasting weather, *always know your terrain*. Many times all the conditions may be right for a particular weather event to occur, but it doesn't simply because orographic features influenced the weather pattern (recall the example of freezing rain in the valley). When considering fronts, recall that warm fronts have a slope of about 1:200, so icing conditions are often found to exist as far as 300 statute miles or more ahead of the surface warm front. Icing may be encountered in cloud or below cloud where freezing precipitation occurs. Cold fronts, although not commonly associated with surface freezing precipitation, can produce freezing precipitation aloft. In addition, the sharper slope of cold fronts can often produce clouds of greater vertical development, and consequently higher LWC and larger droplet environments. Icing near cold fronts is often observed 25 to 130 statute miles behind the surface cold front. Occluded fronts are also producers of icing conditions and should be considered in you flight planning.

Figure 9 is an idealized picture of the airflow through a typical midlatitude cyclone. It can be used as a model to assess your particular weather situation. Notice the *warm conveyor belt* ahead of the cold front and the *cold conveyor belt* below the sloping warm front. These are the main air streams usually observed. An assessment of the strength of the surface winds can give you a rough idea of how strong the flow around a cyclone is. In addition, always look to see what the source of the airflow is. If warm moist air (high temperatures and dew points) from the Gulf of Mexico or the east coast is riding up over cold air that is driving down from the north, you can expect lots of moisture and the potential for severe icing conditions in cloud and precipitation. A final point on cyclones is that maximum precipitation is often observed to the west and northwest of a surface low pressure center. Flight plan carefully around this area because although it is not usually characterized by strong lifting, for reasons beyond our discussion here, it is a region conducive to the formation of SLD.

After developing a good mental picture of the surface weather, a quick look at the upper air charts can give you a good idea of the weather aloft. The 850mb, 700mb, 500mb and 250mb correspond roughly to 3000 ft, 10 000 ft, 18 000 ft and 32 000 ft respectively. A detailed discussion of the information contained in these charts is beyond this paper, but a couple points are worth while mentioning. By looking at any of the charts you can see stations plotted with wind barbs and numbers. Aside from pertinent information given on wind, on the top left of the station plot you will find temperature and on the bottom left you will find the temperature-dew point spread (otherwise known as the dew point depression). If the dew point depression is 5 °C or less, you can probably

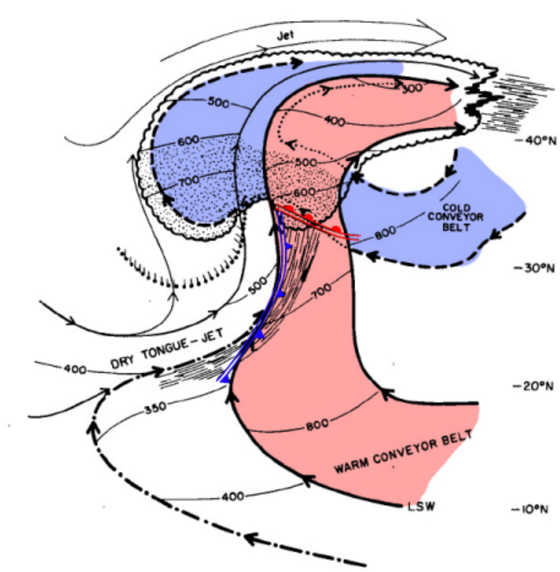

***Figure 9** – Airflow through a typical midlatitude cyclone. (Adapted from Carlson, 1980)*

expect to find cloud in this region. This is a first step in assessing where clouds are likely to exist along your route of flight. If you find that clouds are likely to exist through a considerable depth of the atmosphere, expect the possibility of lots of icing. One downfall to these upper air charts is that they have poor spatial and temporal resolution. They are based on atmospheric soundings taken across the continent at 00Z and 12Z, and the stations are usually several hundred kilometres or more apart. They cannot give a detailed picture of the weather, but with a little bit of extrapolation they can provide a good estimate of current weather aloft. ADDS also provides forecasts for these upper air charts.

Once you have formulated a general picture of the weather, you can begin to look at specifics. Check Graphical Area Forecasts (GFA), Terminal Area Forecasts (TAF), AIRMETS, SIGMETS and Significant Weather Charts (SIGWX) for your route of flight. GFAs give explicit information on clouds and weather as well as locations of forecast icing and freezing level. Take note of the <u>areal extend of clouds</u>, <u>cloud tops and bases</u>, <u>frontal positions</u>, <u>precipitation</u> and <u>freezing level</u> along your route of flight. *If you know nothing else before you leave the ground, know these 5 items!* These are all very important in planning your outs. Confirm that TAFs are consistent with the GFA. Generally TAFs are more detailed and location specific, so if discrepancies exist, make sure you understand why. Also confirm that METARs are consistent with forecasts and check to see if any of the precipitation types discussed earlier exist. If they do, look at surrounding stations to see if they are reporting the same type of weather. If you suspect freezing precipitation or significant SLW aloft, your best option may be to avoid the area altogether. Also remember that every weather condition occurs for a reason. Identify this reason and plan for the possibility that the current observations may change or move to another region. Two other products available on ADDS are the Current and Forecast Icing Potentials (CIP/FIP). These products provide an assessment of the likelihood of encountering icing along your route of flight. They do not provide any information on severity but can give you insight as to where icing conditions are most probable.

The final step in checking the weather is to look for Pilot Reports (PIREPS) along your route of flight. Pay particular attention to time, altitude, type of aircraft and severity of icing. Remember that icing severity is subjective as well as aircraft dependent, so put icing reports into context. Also remember that icing, particularly severe icing is very transient in nature. What existed as little as 5 minutes ago may not exist right now. This has been demonstrated through the review of PIREPS during post-accident investigations. Certain features however, such as fronts, tend to be somewhat quasi-steady so icing PIREPS can to some extent be extrapolated with the front.

Filing the flight plan

With weather in hand you are ready to file your flight plan. You may find that your proposed route of flight will take you into hazardous icing conditions. In this situation it may either be advisable not to go, or to take a different route that will keep you out of the bulk of icing conditions. The following are a few tips that can help you flight plan safely.

The first place to start when anticipating icing conditions is to know your aircraft. Be familiar with all the systems, in particular the ice protection systems. Also be cognizant of your aircraft's performance limitations. Piston aircraft usually cruise at 75-85% power, which reduces their thrust margin for climbing out of icing conditions should they occur. Keep in mind what the cloud tops are and know whether your aircraft can climb above them. Realize that an iced wing will not climb as efficiently as a clean wing. If climbing above cloud tops is not an option, examine the possibility of descending to a lower altitude where temperatures are above freezing or cloud bases are high enough that you can get below. Be mindful however of your Minimum Enroute Altitude (MEA) and ensure that a descent will not create a risk of flying into terrain. If you expect to encounter a front, penetrate the front at a 90 degree angle to minimize your exposure time. If flying along a mountain, or elevated terrain, where the wind is flowing at an angle to the ridge line, stay to the leeward side where descending air is free of clouds and SLW. In both cases a minor diversion can significantly reduce your risk of encountering icing. In any event, *always have an out for every stage of the flight!* It is much easier to think of one on the ground than in the air, when your time is running out.

Preparing the aircraft

Once you're ready to go, complete a final check of the aircraft. Make sure that all the surfaces are clean, including wings, horizontal stabilizer, vertical stabilizer, fuselage and pitot/static ports. Also make sure that no ice has collected in the cavities of the movable surfaces which would inhibit full deflection of control surfaces. Ensure that pitot/static ports are being properly heated and check to make sure that de-icing/anti-icing equipment is properly functioning. Ground de-icing/anti-icing may be necessary. Guidelines and procedures for ground icing operations can be found on Transport Canada's web page (given at the end of this paper).

Before take-off, brief the possibility of icing and have a plan. Review the weather for the departure aerodrome and confirm that it is as expected. A deterioration or change in weather conditions may warrant the cancellation of your flight, even if this is decided as you taxi onto the runway. As well, make sure that you have easy access to the weather along your route and review the relevant items along every phase of your flight.

In-Flight Strategies

The topic of in-flight strategies can be broken down into two categories, monitoring the weather and flying in ice. We will begin by looking at avoidance techniques while in the air and finish with examining some strategies that you can use to cope with an icing encounter. The following is only a brief description of the topic. A much more detailed description of flying procedures in ice can be obtained through the NASA In-Flight Icing Training for Pilots (CD and videos referenced at the end of this paper).

Monitoring the weather

Monitoring the weather is a crucial part of flying, no matter what the season. It should become a natural part of your routine much like the periodic check of flight and engine instruments. The concept is quite basic and provided you remember your flight planning techniques, it can be accomplished in minimal time. It is understandable that cockpit workload can be tremendous, particularly when flying single pilot IFR in ice. If the situation becomes overwhelming, remember your outs and use them. There is no shame in landing short of your destination to hold for weather or to take a moment to better analyze the situation. Don't make weather the last on your priority list.

The primary purpose of Air Traffic Control is to ensure the smooth and safe flow of traffic throughout controlled airspace. Although some weather information may be obtained from these centres, your best option is usually to contact Flight Service (126.7 MHz) in Canada or Flight Watch

(122.0 MHz) in the United States. Periodically contact these services to update weather along your route. Of interest to you are recent PIREPS, METARS and updated forecasts. PIREPS will give you information on what other pilots have encountered. Remember, icing is transient and PIREPS can be subjective, but used in context they can be very helpful. METARS contain several pieces of information that can help you assess the weather situation. Cloud bases and visibility will help you determine whether your destination and alternate airports are holding their forecasts as expected. They can also provide information on precipitation to assess the potential for icing conditions aloft. Temperature changes and wind shifts, often followed by gusty conditions, can help you assess where fronts are located if expected along you route of flight. Finally, explain your intentions to the flight service specialist and ask him/her to interpret the weather for you. They have access to products such as satellite imagery and radar composites that can help give you a better picture of the weather.

In addition to updating weather along your route, be aware of the weather you are currently in. If radar equipped, check for regions containing precipitation echoes and try to avoid them. These can be clues that SLD or freezing precipitation exists in the area. Be sure to monitor your outside air temperature gauge and confirm that the temperature is what you expected. If your only out was to descend below the freezing level, and the freezing level begins to drop, reassess your outs and make sure you don't get trapped. Also, if flying in and out of clouds, look for visual cues such as building and newly developing cloud tops and avoid them. Young clouds are more likely to contain SLW.

The rules for checking the weather along your route are simple: Confirm that the weather is holding as expected, reassess your outs and don't get trapped!

Coping with icing

There are typically 6 options that you have when you encounter ice (NASA In-Flight Icing Training for Pilots). These are to *climb, descend, continue, divert, return* or *declare an emergency*. It is important that you never forget that these choices are available to you. With proper flight planning you should already have an idea of what you intend to do. If icing conditions are minimal, you may decide to continue and monitor the conditions to make sure that they don't get any worse. Recall from **Figure 3b** that 90 % of icing encounters are less than 50 statute miles in horizontal extent. You can also descend below the freezing level (being mindful of the MEA) or climb above cloud tops. If you decide to climb, be cautious near cloud tops because this is where the worst icing conditions can occur. Even if you can't top the clouds, recall from **Figure 3a** that in 9 out of 10 times, a change in altitude of 3000 ft will take you out of the icing conditions. If you start to pick-up ice, don't wait until you have used all available power. Piston aircraft generally have a smaller thrust margin than turbine aircraft, so quick and accurate pilot decision making skills are imperative. When climbing or descending, be sure to fly at a safe airspeed recalling that stall angle can be significantly reduced. Also, keep bank angles to a minimum when ice has been accreted; increasingly icing accidents are being attributed to control anomalies such as wing stalls and tail stalls. Diverting to an alternate or turning around are also viable options. Presumably the icing conditions where you came from are better than those that you are in. Examine these as possibilities if climbing or descending is not an option. Finally, when all else fails, be aware that you can always declare an emergency. This will give you priority handling and may be your only way out. The consequences of declaring an emergency are negligible compared to those of a crash due to icing. Remember that ATC's primary function is to ensure the smooth and safe flow of air traffic, and that only you know exactly what the weather is like where you are. If you feel that the present weather conditions may adversely affect the safety of your flight, exercise your duties and responsibilities as pilot in command and keep your aircraft flying safely.

Detecting ice can be difficult, especially clear ice at night. Look for other cues to help you determine whether ice has been accreted. This begins with having a good knowledge of your aircraft's performance. Loss of airspeed for a given power setting or unusually high power settings for the same airspeed, decreased climb rate and changes in control authority are all possibilities in helping you detect ice. The latter is an extremely important point, but will not be covered in detail in this paper. I will only take a moment to mention it, but I strongly suggest that every pilot who is flying in icing obtain the NASA icing training package. This is an excellent resource and focuses much of its time on detecting and recovering from control anomalies. I will only say that there are basically two types of stalls that result from icing, wing stalls and tail stalls. The indications of either can be quite similar, but the recovery techniques are virtually opposite. The use of an improper recovery procedure can very quickly aggravate the stall and prove to be fatal.

Detecting icing also includes looking for SLD. Signs of SLD include runback and ridging beyond the protected surface, ice on the pilots' side windows and on aircraft components which do not normally accrete ice (such as aft on the spinners). If SLD is suspected, exit the conditions immediately. Remember that your aircraft is not certified into SLD and that every encounter will be different.

General practice when flying in ice with pneumatic boots is to allow ¼ - ½ inch of ice to accrete before cycling the boots. Typically this was done because of a phenomenon known as *bridging*, where small amounts of ice would not break-off and would prevent further cycling of the boots from removing newly accumulated ice. Extensive studies by NASA have shown that ice bridging is no longer a concern for modern boots. The recommended procedure is to cycle the boots as soon as icing is encountered, and to continually cycle them thereafter. This procedure may leave more residual ice on the wings between boot cycles, but subsequent cycles will remove this ice. Furthermore, the performance degradation resulting from this residual ice is preferential to that of allowing ice to accumulate ¼ - ½ inch. It will also keep the flight characteristics of the airfoil more consistent.

Another argument in favour of cycling the boots continually is that of ice accretion on the tail. Recall from the section on *Icing Dynamics* that smaller objects tend to accrete ice faster than larger ones. On most aircraft the leading edge radius of the horizontal stabilizer is smaller than that of the wing section. If ¼ - ½ inch of ice has been allowed to collect on the wings, it is quite probable that even more has collected on the tail; and because the tail surface area is smaller the performance penalties may be proportionally greater. This can lead to unexpected control anomalies like a tail stall. This also raises another point. When temperatures are below 0 °C in cloud, even if ice is not observed on the wings, be mindful that it may already have accreted on the tail.

The information in the previous two paragraphs is for educational purposes only. Some manufacturers have already changed their POHs and AFMs to include the procedure of cycling the boots continually when in ice. In any event, <u>always</u> use your POH or AFM as the final authority and follow company operating procedures.

Summary and Study References

This document contains some information on the basics of icing. I have tried to make it as comprehensive as possible, but anyone intending to fly in ice is strongly advised to study the references given below. With the exception of some of the icing physics given near the beginning (usually not covered in standard texts), all the information in this document is readily accessible to anyone willing to study it. I have tried to find a balance between the "nice-to-know" and the "need-to-know". Some of the information contained within this paper will not help you to fly, but it will help you to understand the weather better. I have purposely left out detail on the *In-Flight Strategies* because I feel that a paper of this length could not do this topic justice.

The information in this document is for educational and reference purposes only. Always use your POH, AFM and company operating procedures as the final authority. And remember that meteorology is by no means an exact science. It is impossible to cover every icing scenario, so expect that every icing encounter will be different.

Anyone wishing to contact me for further information, or to contribute comments, is more than welcome to email me at nick@aerosafety.ca .

The best resources I found for pilots wanting to study aircraft icing are the following:

- NASA In-Flight Icing Training for Pilots (CD + 3 DVDs) – available through Sporty's Pilot Shop for only $10 US < http://www.sportys.com/takeoff/ >
- In-Flight Icing, 2nd Edition, Perkings and Reike – available through Sporty's Pilot Shop for only $10 US < http://www.sportys.com/takeoff/ >
- Aircraft Icing Handbook, New Zealand Civil Aviation Authority – available free on the web at < http://www.caa.govt.nz/fulltext/Safety_booklets/Aircraft_Icing_Handbook.pdf > (or just search "Aircraft Icing Handbook" on Google)

I must admit that I was very impressed with the quality of these three references and the price demonstrates their commitment to enhancing the safety of aviation. If you study no other references study these!

Other references include:

- Aircraft Icing: A Pilot's Guide, Terry Lankford – available at most pilot shops
- Aviation Weather Services, NOAA (describes the U.S. aviation weather resources) – available for purchase at most pilot shops or it can be downloaded free from the web
- Weather Flying, Robert Buck – available at most pilot shops

Some useful web pages:

- Environment Canada Weather - http://weatheroffice.ec.gc.ca/charts/index_e.html
- U.S. Aviation Weather Center - http://aviationweather.gov/
- Aviation Digital Data Service - http://adds.aviationweather.noaa.gov/
- Nav Canada Weather - http://www.navcanada.ca/
- Research Applications Program (RAP) - http://www.rap.ucar.edu/weather/
- Transport Canada Ground Icing Manuals - http://www.tc.gc.ca/civilaviation/general/exams/guides/menu.htm

There are many other useful website out there, you just have to do a bit of searching

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