contract with the National Aeronautics and Space Administration.

Glossary

CCN cloud condensation nuclei
emission index measure of aircraft emission in units grams of exhaust per kilogram of fuel burned
IN ice nuclei
ICAO International Civil Aviation Organization
LS lower stratosphere
NO_x reactive oxides of nitrogen ($NO_x = NO + NO_2$)
ppmv parts per million by volume
pptv parts per trillion by volume
SO_x reactive oxides of sulfur ($SO_x = SO_2 + SO_3$)
UT upper troposphere

See also

Chemistry of the Atmosphere: Chemical Kinetics; Gas Phase Reactions; Principles of Chemical Change. **Climate:** Overview. **Contrails**. **Global Change:** Ozone Trends. **Soot**. **Stratospheric Chemistry and Composition:** HO_x; Reactive Nitrogen (NO_x and NO_y). **Stratospheric Water Vapor**. **Tropospheric Chemistry and Composition:** Aerosols/Particles; Carbon Monoxide; Sulfur Chemistry, Organic.

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AIRCRAFT ICING

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Introduction

Aircraft icing is the accretion of supercooled liquid onto an airplane during flight. Accreted ice adversely affects flight; thus, it is an important component of an aviation weather forecast. Meteorology associated with in-flight icing begins with the microscale, addressing growth of supercooled droplets and their collision with and adhesion to airframes. Cloud-scale and mesoscale processes control the amount and distribution of supercooled liquid water. Synoptic weather patterns govern the movement and overall location of icing environments. Any discussion of aircraft icing must also include the development and use of numerical weather prediction models as well as *in situ* and remote sensors for icing detection, diagnosis, and forecasting. There are isolated cases of snow and frost adhesion during flight, but since these rarely occur they will not be discussed here. Similarly, precipitation or frost adhering to the wings of an airplane prior to takeoff, and carburetor icing, will not be covered.

Effects on an Aircraft

Although the basic concept of in-flight icing is a simple one, the processes contributing to icing, and the results of icing, are at once quite complex and fascinating. Meteorologists, aerospace engineers, and pilots need and want information about icing because it can adversely affect the flight characteristics of an aircraft. Icing can increase drag, decrease lift, and cause control problems. The added weight of the accreted ice is generally a factor only for light aircraft.

Aircraft can fly in icing conditions, and to do so legally they must first be certified. For certification of a particular type of airplane, it must be flown in a range of natural icing conditions and demonstrate that these conditions result in no significant effect on the airplane's performance. The range of conditions was first developed from measurements obtained in the 1940s and is illustrated in **Figure 1**, which was designed to envelop 99.9% of icing conditions found

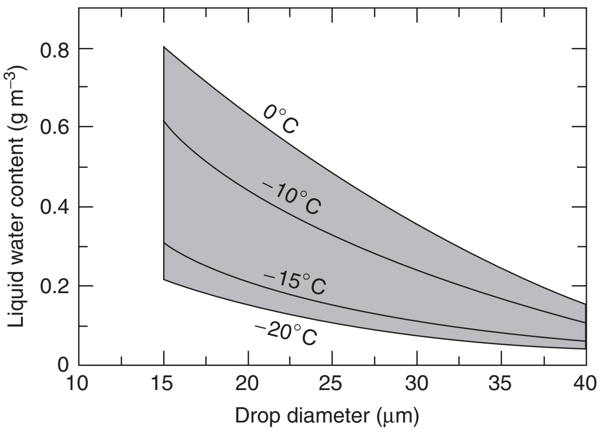

Figure 1 Icing envelopes defined by liquid water content, droplet size, and temperature. The shaded areas denote the limits of these environmental parameters in which aircraft must be able to fly safely to be certified for flight into icing conditions. (From FAA Federal Aviation Regulations Part 25, Appendix C.)

in stratiform clouds. More recent studies have confirmed that the indicated range provides reasonable limits for certification, although, as will be presented in a later section, it does not address the problem of large supercooled drops.

Certified aircraft are commonly equipped with devices that either serve to prevent ice from adhering to the airframe or remove it once it has adhered. Such anti-icing or de-icing equipment may be deployed manually or through an automatic system triggered by an icing detection probe. Equipment includes pneumatic 'boots', heat, and liquid. All three can be applied to the leading edges of the wings and tail, and occasionally to propellers.

Tailplane icing is a subset of icing and refers to icing that accretes on the vertical and horizontal stabilizers. It is not necessarily caused by unique atmospheric conditions but is usually considered separately because it results in vastly different response of the airplane from that produced by icing on the wings.

Icing tends to affect general aviation less than commuter or air carrier operations; there are several reasons for this. The smaller aircraft included in the general aviation category tend to fly at lower altitudes where icing is more prevalent. Those aircraft may have less de-icing capability and reserve power in case of encountering icing conditions, and their pilots may have less experience of operating under icing conditions. Air carriers tend to quickly penetrate icing-bearing clouds on ascent and descent from airports and cruise at altitudes far above those at which icing occurs. Commuter aircraft are caught in the middle, in terms of both their ability to handle ice and the altitudes at which they fly. With the burgeoning business in this area, they find themselves susceptible to icing and need accurate forecasts.

Severity and Intensity of Icing

Icing is currently classified into four severity categories: trace, light, moderate, and severe. Severity is a combination of the state of the icing environment, the aircraft's response, and the pilot's assessment of the response. **Table 1** shows descriptions for icing severity that are being adopted for official use by the FAA.

Even with these severity descriptions, there is as yet no official quantification of environmental parameters. The most important parameters are the liquid water content, outside air temperature, and droplet size. The more liquid water there is, the more is available to accrete on the airframe, and thus higher liquid water contents are associated with more severe conditions. Temperature controls what happens to that liquid once it impacts the airframe – either it freezes in place or it runs back along the surface to possibly unprotected areas. Droplet size controls the collection efficiency of those droplets onto the airframe. Overall, droplet size is not as important as liquid water content or temperature in determining

Table 1 Icing severity descriptions

Category	*Description*
Trace	Ice becomes perceptible. Rate of accumulation is slightly greater than 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 1 hour).
Light	The rate of accretion may create a problem if flight is prolonged in the environment (over 1 hour). Occasional use of de-icing/anti-icing equipment removes/prevents accretion. It does not present a problem if the de-icing/anti-icing equipment is used.
Moderate	The rate of accretion is such that short encounters become potentially hazardous and use of de-icing/anti-icing equipment, or diversion, is necessary.
Severe	The rate of accretion is such that de-icing/anti-icing equipment fails to reduce or control the hazard. Immediate diversion is necessary.

severity until droplets reach drizzle sizes, with diameters exceeding $\sim 50\,\mu m$. Thus, environments with high amounts of liquid water with large droplet diameter at warm (but supercooled) temperatures would represent the most hazardous conditions for aircraft icing. Research is being conducted to determine appropriate limiting values for these parameters to define each severity category. To be useful, the definitions must relate atmospheric conditions to observable information as well as effect on flight.

Types of Icing

There are two main physical types of icing: glaze and rime. Mixed icing is a combination of the two. Rime ice is brittle and opaque and tends to grow into the airstream. It is formed as the droplets freeze immediately upon impact. Glaze icing, sometimes referred to as clear icing, can be nearly transparent and has a smoother surface, sometimes with a waxy appearance. It is formed when the droplets deform and/or flow along the surface prior to freezing. Glaze icing can be more serious to the aircraft than rime since it tends to run back along the airframe, covering more surface area than rime icing — perhaps flowing onto and adhering to unprotected areas. Glaze icing can be hard to see from inside the aircraft, so that the pilot may be unaware of ice buildup. Mixed icing often occurs in layers, similar to wet and dry hailstone growth, as a transition from rime to clear conditions is encountered. These icing types are illustrated in **Figure 2**.

The type of icing is related to the air temperature, the liquid water content, and the size of the droplets. Glaze is generally associated with higher temperatures, higher supercooled liquid water (SLW) contents and larger droplets. Rime is usually created at lower temperatures, low SLW contents, and small droplet size. There are also effects dependent on the airplane itself, including wing shape, airspeed, and type of de-icing/anti-icing equipment.

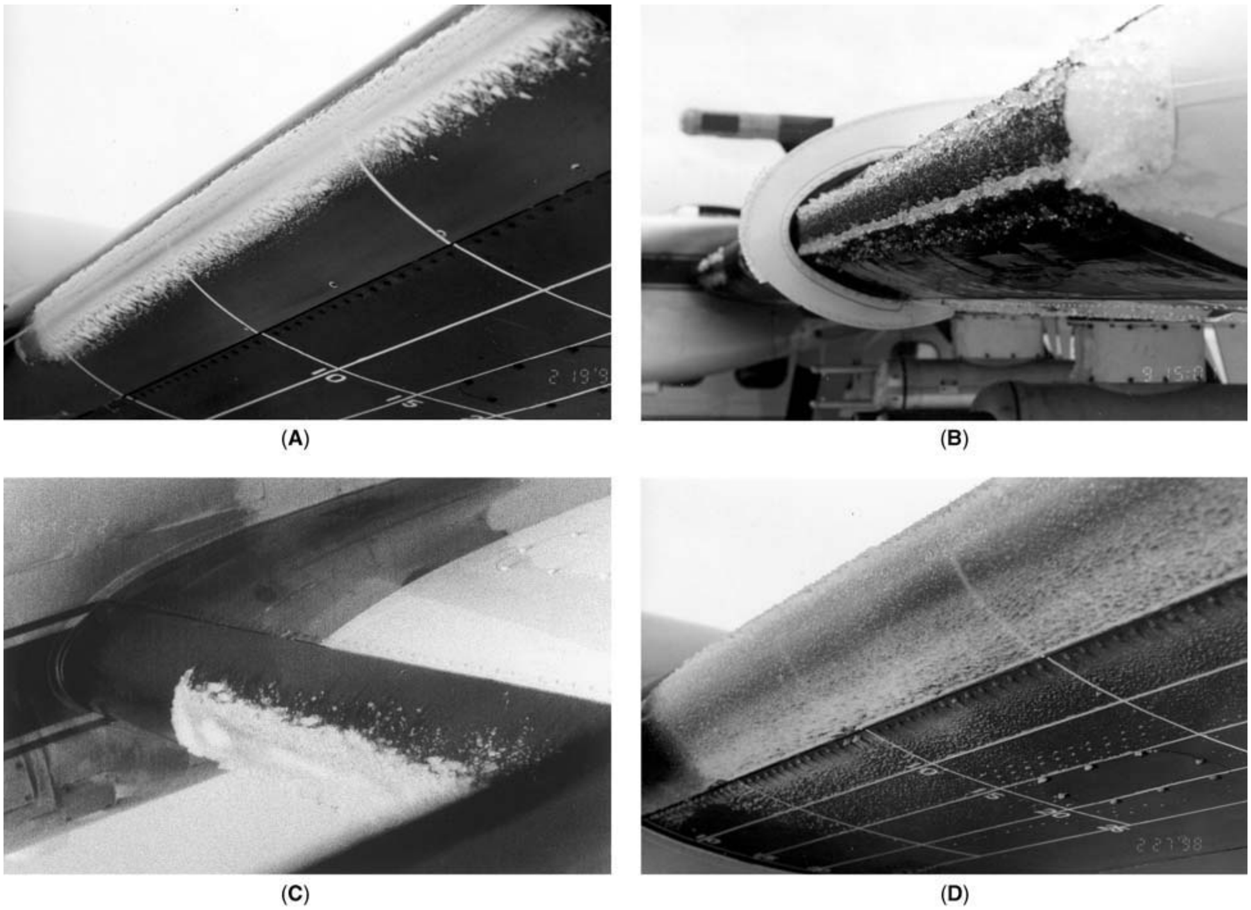

Figure 2 Post-flight photographs of ice encountered by the NASA Glenn Research Center's instrumented Twin Otter aircraft. The leading edge of the left wing is shown in each photograph: (A) light rime ice, (B) severe glaze ice, (C) moderate mixed ice, (D) supercooled large droplet ice. Note how much farther aft the ice in (D) has accreted compared to the other types. (Photographs courtesy of NASA Glenn Research Center.)

Location and Frequency of Icing Conditions

Since icing occurs in clouds or precipitation at temperatures below 0°C, any icing climatology must be associated with cold, cloudy conditions. **Figure 3** shows that icing frequency is most strongly related to latitude in the contiguous United States, with some preference for the northeastern part of the country. Icing-related fatal aircraft accidents average approximately 30 per year in the United States, with the highest incidence in the winter months. Alaska has by far the highest accident rate, followed by the northwest mountains, Great Lakes, western Pacific states and the central states.

The average altitude of icing environments is around 3000 m above mean sea level (msl), with few encounters above 6000 m. Cumuliform clouds, with their greater depth and transport of significant liquid amounts to higher altitudes, have on average higher altitude coverage than stratiform clouds. Frequency of icing 'PIREPs' (pilot reports) by time of day is a direct reflection of the frequency of flights, with few reports overnight. The weekly pattern also follows air traffic trends, with most reports on Tuesday through Thursday.

Light icing is the most frequent severity category reported by pilots, accounting for ∼60–70% of all reports. Severe icing, which indicates a condition in which flight cannot be sustained, is reported in only a few percent of cases. Rime icing is reported much more frequently than glaze or mixed, comprising ∼70–75% of reports. For both icing type and severity, the largest joint frequency is for light rime icing, which covers nearly half of all reports.

Relation of Icing to Weather Features

Icing takes place in clouds or precipitation and is thus closely related to weather features providing such conditions. Most PIREPs of icing occur near fronts. Regions ahead of or near surface warm fronts are favorable icing regions if temperatures are in the right range (∼0 to −20°C), since they provide widespread lifting of generally moist air. Cold fronts also provide opportunities for icing, with narrower regions of more intense lifting near the surface front. Moist, maritime air masses are associated with higher frequencies of icing PIREPs, whereas continental air masses, especially those well behind arctic fronts, have fewer reports. Topography also influences icing, providing

Figure 3 Frequency of icing expected over the contiguous 48 states of the United States in February. Frequency is expressed as percentage of total time available. These data are for February 1992 through 1997, for altitudes <3000 m above msl. The plots were constructed by correlating icing pilot reports to surface weather measurements, then extrapolating the icing pilot report frequency to the entire month, to account for overreporting in high air traffic areas, and underreporting during nighttime and in low or no air traffic areas. (Courtesy of Barbara Brown, National Center for Atmospheric Research.)

local sources of uplift. For example, cold fronts progressing southward through the central United States often provide widespread icing conditions along the front range of the Rocky Mountains from Wyoming through New Mexico. Cold, moist air is forced up the gentle slope leading to the steep mountain range. Lake-effect storms tend to be efficient in forming snow, but near the leading edges of lake-effect clouds, where ice has not yet begun to form, significant supercooled liquid water concentrations can be found.

One might assume that icing will not be present aloft where there is significant precipitation at the surface due to scavenging of cloud liquid water. However, examination of PIREPs has not borne this out; the chances are about even that a PIREP will be associated with surface snow or rain as opposed to no precipitation. PIREPs of moderate or greater severity combined with clear or mixed icing type are significantly more likely to be reported near locations of surface observations of freezing precipitation than those locations with rain, snow, or no precipitation. This feature can be used by the forecaster as a clue for potentially hazardous icing and will be discussed more thoroughly in a later section on large droplet icing.

Microphysical Characteristics

Measurements of the microphysical characteristics of icing environments have been obtained from the 1940s to the present. Temperatures range from 0°C to below −25°C, with a mean around −10°C. Few icing encounters occur at temperatures below −20°C. At temperatures above about −5°C, adiabatic compression of air may increase the actual temperature along the leading edges of the airframe to above freezing; typical dynamic heating corrections are 1–2°C for small, slow aircraft, to as much as 6–8°C or higher for large, faster-flying air carriers.

Liquid water content (LWC) of icing environments tends to be, on average, fairly low. In convective clouds, 90% of the values are <0.5–$0.7\,\mathrm{g\,m^{-3}}$ and for stratiform cloud <0.3–$0.5\,\mathrm{g\,m^{-3}}$. Maximum values for LWC are typically ~ 1.2–$1.3\,\mathrm{g\,m^{-3}}$, but can reach higher values in deep convective clouds. The distance over which certain LWC values continuously exceed certain limits decreases with increasing amount of liquid; continuous LWC $>0.5\,\mathrm{g\,m^{-3}}$ was limited to distances <13 km in one study, whereas in the same study one encounter had LWC $>0.1\,\mathrm{g\,m^{-3}}$ persisting along 83 km of flight path.

Droplets are typically small, with average mean diameter or median volume diameter usually between 10 and 20 μm. Maximum values for mean diameter are 30–50 μm, depending on the data set. Cumuliform clouds tend to have larger droplets than stratiform clouds, and clouds in continental areas have smaller droplets than those in maritime areas. Liquid water content and droplet size generally increase with altitude in single cloud layers but the behavior is less predictable in multilayered clouds. These are general guidelines — individual clouds can and do vary considerably from one another, and variations occur within clouds.

There is only limited anecdotal evidence that ice crystals will adhere to an airplane in flight. High concentrations of ice crystals alone, as in cirrus thunderstorm anvils, have been related to engine problems due to ice ingestion, but they are not an airframe icing problem. A surprising number of icing encounters are in mixed-phase conditions, that is, when ice crystals are present along with the supercooled liquid water. This appears to be the norm rather than the exception, and has implications for remote detection and forecasting. Mixed-phase conditions are usually thought to represent a transitory state as ice crystals will tend to grow at the expense of the liquid droplets. However, in a case with sufficient moisture supply and updraft speed, enough condensate can be produced for both deposition on ice and condensation on droplets to occur.

Supercooled Large Droplet Icing

It has been recognized for some time that supercooled large droplets (SLDs), which are those with diameters exceeding 50 μm, pose an especially serious threat to flight. Their larger size means they are not as likely as small droplets to be carried around the airframe with the airstream but more readily impact on the airframe. SLDs can impact farther aft than small droplets, which means that they may land on and freeze on areas not usually protected by de-icing or anti-icing devices. The larger droplets may also flow along the aircraft before freezing, sending them to these unprotected locations. Roughness resulting from this type of ice accretion can create a greater aerodynamic penalty than that at the very forward edge, near the ‘stagnation point’ where the airflow splits to go under or over the wing. Cases of increased degradation of performance due to flight in SLD conditions are well documented for several research aircraft.

There are two general situations for formation of SLDs. The first is the classic freezing rain process, by which snow forms aloft, falls into an intruding warm ($T>0$°C) layer, melts, continues to fall into lower cold air ($T<0$°C), and becomes supercooled, ready to adhere to an airplane. This is a relatively easy forecasting problem since it requires a specific thermodynamic profile. The other general case is formation of SLDs by coalescence of liquid drops, and is not so easily recognized using operationally available data sets. Wind shear (differences in wind speed and/or direction) at cloud top in stratiform clouds may encourage the formation of SLDs, but specific mechanisms for SLD formation in these cases have not yet been identified. There is some evidence that minimum thresholds of liquid water content must be exceeded for drizzle formation to occur: 0.2–0.25 $g\,m^{-3}$ in continental clouds and around 0.1 $g\,m^{-3}$ in maritime clouds.

The observation of freezing precipitation – freezing drizzle, freezing rain or ice pellets – at the ground can provide an important clue for SLD conditions aloft. This makes physical sense since all three are supercooled (or already frozen) large drops: if they are present at the surface, they must be present for some depth above the surface. The more difficult part of using this to diagnose SLD conditions aloft is to determine how far aloft the SLDs will be present. Knowledge of the moisture and thermal structure of the atmosphere is needed to infer this depth.

Detection of Icing Conditions

In situ detection of icing is done visually or by the use of instrumentation. Pilots generally have a poor view of the wings of their aircraft, so they may use the icing accreting on windshields, wipers, or pitot tubes near the nose of the aircraft to assess the presence and amount of ice. The pilot can also notice changes in aircraft performance due to icing as described in the table of severity indicators. Icing detectors warn the pilot when ice is accreting on the aircraft. In some cases these instruments are sensitive enough to provide an early warning before the ice becomes noticeable to the pilot. These airframe-mounted detectors are a fairly mature technology, although new systems are still being developed. Examples of detector types are those that can be flush-mounted on the wing and detect differences in capacitance on the surface, or have a vibrating rod protruding into the airstream that detects the difference in resonant frequency as ice accretes. Special camera-like systems that use infrared or other wavelengths of light are also being developed. The advantage of *in situ* systems is that they provide a definite detection of icing conditions. However, they have the drawback that the aircraft must necessarily be within the icing environment, and in many cases that is not a desirable place to be.

The use of remote sensors for detecting icing is in a relatively young stage of research and development. At this time there is no one instrument that will remotely and accurately determine where supercooled liquid resides in the atmosphere. Research into the proper interpretation of remote sensor data for icing applications is very active at this time. TDWR (Terminal Doppler Weather Radar: C-band, 5 cm) and NEXRAD (Next Generation Weather Radar: S-band, 10 cm) operational radars were not specifically designed for icing detection, but they may yield information that, when combined with that from other sources such as numerical weather prediction models, satellite imagery, or surface observations, provides clues to the location and intensity of icing. Altering scan strategies to sample the lower atmosphere more effectively, or retrofitting these radars with polarization capability, may aid in their utility as icing diagnosis tools. Short–wavelength radars (such as K-band, 0.86 cm or W-band, 3 mm) have shown potential for detecting icing conditions, especially in nonprecipitating clouds. Dual- or triple-wavelength systems, using combinations of W-, K-, X-, and longer wavelengths, also have shown promise in quantifying liquid along the radar beam. These systems take advantage of the differences in attenuation of microwave radiation by atmospheric liquid at the different wavelengths.

Since icing often occurs in mixed-phase conditions, some means must be available to discriminate between ice and liquid in the radar data. Use of reflectivity alone, even with accompanying temperature information, is not sufficient. Polarization is one method by which this may be done through determination of the shape of the hydrometeor.

Multichannel microwave radiometers, which passively detect radiation emitted from atmospheric constituents, have also been shown to be useful in identifying icing aloft. Their drawback is that they currently do not identify the altitudes at which icing exists (although this is an active area of research), and whether the detected liquid is supercooled. As with radar data, combining radiometer-based information with that from other instruments can help the forecaster gain insight into the nature of the icing environment.

Multispectral Geostationary Operational Environmental Satellites (GOES) show great promise as icing diagnosis tools. Several algorithms have been developed that use combinations of visible and long- and short-wavelength infrared channels to determine locations of supercooled liquid cloud tops. These algorithms will not diagnose where all icing conditions exist or are absent; for example, ice-bearing cirrus may overlie a supercooled liquid cloud and prevent its detection, or a supercooled liquid layer may be present above a cloud consisting predominantly of ice crystals.

Nevertheless, satellite-based techniques provide the forecaster with an additional clue as to where icing resides and should be used in combination with other data. Methods have also been devised to use microwave information from satellites to quantify the total integrated amount of atmospheric liquid water content over oceans. Progress in adapting these to overland use is slow, owing to the wide variations in background radiative emission from the Earth's land surfaces compared to the relatively constant values over water. These data could be combined with other observations or model outputs to provide the needed information on the location and nature of icing conditions in clouds.

Forecasting Icing Conditions

Forecasting in-flight icing is the same as predicting the presence of supercooled liquid water in clouds – not exactly on the list for undergraduate weather forecasting laboratories. Following a 'forecast funnel' process, the forecaster seeks

Clouds or precipitation
  Favorable temperature regime ($<0°C$, $>-20°C$)
    Lift to create liquid
      Lack of significant ice to encourage glaciation

Various guidelines linking weather features observable on the synoptic or mesoscale with the occurrence of icing conditions have been used with some success. However, a better route is to apply knowledge of the atmosphere to the available information. Knowing what creates and depletes liquid, in combination with information about where clouds are expected and the temperature structure of the atmosphere, should provide a much more reliable and geographically robust prediction. These concepts can also be incorporated into automated systems that provide the forecaster with initial guidance or the nonmeteorologist with a reasonable 'final answer' of where to expect icing.

Current icing forecasting methods vary but they share some common characteristics. They tend to be human-intensive, time-consuming, and somewhat subjective, and they have output formats that can be difficult to interpret. Until recently, operational weather prediction models did not include an icing product or clouds or liquid water fields. Thus, the forecast problem was to determine, using the available output, where supercooled cloud was likely to be located.

In the absence of explicit information on the locations of clouds, it is possible to make a reasonable forecast using temperature and relative humidity predictions from numerical weather models. The methods tend to produce a maximum probability of detection of icing (that is, where there was a PIREP of icing there was also a forecast of icing) of $\sim 75\%$. The actual threshold values will depend on model specifics such as horizontal and vertical resolution, the treatment of moisture in the boundary layer, and so on. Adjustments can be made to mimic situations where icing probabilities can be enhanced. For example, relative humidity thresholds might be lowered in cases where deep convection is expected, since rising turrets may penetrate altitudes where model humidity is low. Low-level stratiform clouds with relatively warm tops and no overlying cloud layers are especially favorable for supercooled liquid water, and algorithms can be developed to recognize these situations from model-generated temperature and humidity profiles.

With the advent of improved numerical weather prediction models with prognostic cloud liquid water content, the potential exists to determine where icing really exists (as opposed to inferring it from smoothed temperature and humidity fields), and to quantify the hazard in terms of icing severity and type. Generally, cloud microphysical parametrizations are first developed and tested on research models such as the Penn State/NCAR Mesoscale Model (MM5), or the Colorado State University RAMS, run in a post-analysis 'diagnostic' mode. Concepts are then coded and tested for use in the operational models deployed by the US National Centers for Environmental Prediction (NCEP). Currently, the meso-Eta model includes liquid water prediction, and preliminary verification for icing looks promising. The Rapid Update Cycle Model includes a microphysical parametrization with prognostic equations for additional hydrometeor types.

One of the roadblocks to inclusion of cloud liquid water fields in the operational models is the demand for extra and computer power and storage capacity. However, inclusion of an explicit liquid water field is really the only means toward the goal of automated prediction of severity and type of icing.

No one observational tool or weather prediction model provides us with all we need to know about where icing is located, or any of its attributes such as type or severity. Forecasters combine the information from various sources to get the complete story on icing; it makes sense to develop automated algorithms to accomplish the same goal. Automated versions of this human technique are being developed and to date have proved quite successful in diagnosing where icing conditions reside. Predictive capabilities, by which sensor-based icing features are identified and extrapolated forward, represent the means by which this combined approach may be taken into the future. The key to successful icing forecasting lies in understanding the physical processes resulting in supercooled liquid water production, how these processes relate to observable phenomena, and how to combine information from as many sources as possible to gain the most complete picture of the icing situation.

Glossary

Supercooled Refers to liquid water cooled to below 0°C without becoming a solid (ice).

Glaze ice Ice with a translucent, glossy appearance. May be smooth or have embedded lumps. Sometimes referred to as 'clear' ice.

Rime ice Opaque, brittle ice that tends to form 'feathers' into the airstream.

Mixed ice A combination of rime and glaze ice, caused by variations in atmospheric parameters resulting in either type of ice.

Severity Refers to the combination of environmental icing intensity, aircraft response, and pilot interpretation of that response.

See also

Cloud Microphysics. **Cyclones, Extra Tropical**. **Humidity Variables**. **Mesoscale Meteorology:** Overview. **Mountain Meteorology**. **Parameterization of Physical Processes:** Clouds. **Radar:** Precipitation Radar. **Satellite Remote Sensing:** Precipitation; Temperature Soundings; Water Vapor. **Thermodynamics:** Moist (Unsaturated) Air. **Weather Prediction:** Regional Prediction Models.

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AIR–SEA INTERACTION

Contents

Freshwater Flux

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Introduction

The world ocean is a key element of the physical climate system. The ocean contains 97% of the world's water and covers an area of 71% of the globe. As a reservoir, the ocean supplies water vapor to the atmosphere that brings rain and snow over land surfaces. About one-third of the precipitation over