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New Ground Deicing Hazard Associated with Freezing Drizzle Ingestion by Jet Engines

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A new ground deicing hazard is described, consisting of the accretion of freezing drizzle onto jet engine fan blades and cowlings, and subsequent shedding of the accreted ice during takeoff leading to damage to jet engine fan blades. Cases of damage to aircraft from hazardous surface icing conditions at Denver, Colorado and Oslo, Norway are described. The two cases at Denver cost United Airlines over $2 million in damage to 12 B737-300 engines. The hazard is identified as heavy freezing drizzle through examination of National Weather Service observations of upper level temperature and humidity, satellite, radar, and freezing rain sensor data. The official National Weather Service observation during these cases, however, was either light snow and mist or light freezing drizzle. The reason for this misreport and underestimate of intensity lies in the current reporting rules for determining freezing drizzle intensity by visibility and not by precipitation rate. Theoretical relationships are presented that show that the variation in drizzle size distribution and the difference in determining visibility from day and night is the cause of the poor correlation of drizzle rate with visibility.

Nomenclature

dBZ	=	radar reflectivity in dB units (10 log Z) where Z is the radar reflectivity factor
Rate	=	drizzle rate, mm/h
Vis	=	visibility, km
ρ_w	=	density of water, 1.0 g/cm^3
$\Gamma()$	=	gamma function
Λ	=	slope parameter, cm^{-1}

Introduction

ON 31 October 2002, 12 United Airlines B737 aircraft incurred jet engine damage during a winter storm at Denver, Colorado. The damage was primarily bent fan blade tips, and was consistent with ice being ingested into the engines at normal flight engine speeds (Fig. 1, photo of bent fan blades). Total damage was reported by United Airlines as being over $2 million, with one engine requiring total replacement. The damage was noted after the aircraft landed at their destination airports. The aircraft incurring damage departed Denver between 5:00 and 8:00 p.m. Mountain Standard Time (MST) [(1 November, 0000-0300 Coordinated Universal Time (UTC)]. The weather observer at Denver reported mist and light snow during this time period, and also unseasonably cold temperatures (−8°C). While inbound to Denver these aircraft encountered light to moderate icing aloft as given by pilot reports. After landing, the aircraft were deiced at the gate to remove ice buildup that occurred via in-flight ice accretion. The deicing included the removal of any ice from the jet engine fan blades. Once deiced and loaded, the aircraft taxied to deicing pad B (located just west of Concourse B at Denver International Airport, see Fig. 2), and were further examined for ice accumulation due to the reported snow conditions. During this period ground personnel reported the presence of freezing drizzle despite the METAR report of mist and light snow. Denver is a category A airport and therefore had an observer present who augmented the METAR in this case to report snow and mist. An interesting observation for this case was that only the right engines were damaged.

One year later, on 31 October 2003, Denver again experienced a surface icing event (with reported light freezing drizzle) during which additional B737 jet engines were damaged. Another similar case of B737 jet engine damage occurred at Oslo Gardermoen Airport in Norway with Braathens airline in February 2003. This paper examines the weather conditions associated with these cases, and comes to the conclusion that the actual weather condition during the time periods of engine damage in all three cases was most likely heavy freezing drizzle rather than light snow and mist as reported in the 31 October 2002 Denver case or light freezing drizzle as reported during the 31 October 2003 Denver and February 2003 Oslo cases. If the flight crew had been aware of the heavy freezing drizzle

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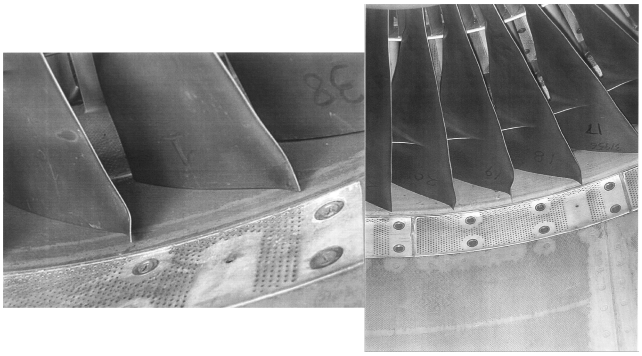

Fig. 1 Photograph of bent fan blades from the damaged B737-300 engines.

Fig. 2 View of Concourse B and United deicing pad at Denver International Airport.

conditions, more frequent run-ups of the engines may have been performed to shed any potential ice accumulation. A stop of operation may also have been decided at an earlier stage. Because the official weather observations did not indicate significant icing, these actions were not taken, and the ice that accumulated during taxi from the gate and during the taxi to takeoff was likely shed during the takeoff rotation, causing the reported damage to the aircraft.

This paper provides an analysis of the weather conditions associated with the Denver 31 October 2002 incident as well as an overall discussion of this event. This incident is compared with the February 2003 Oslo event and the 31 October 2003 Denver case. Possible reasons for the misreporting of freezing drizzle intensity are then given. Finally, a proposed solution to this problem is provided and final conclusions made.

Analysis of Weather Conditions During the 31 October 2002 Surface Icing Event

Jet engine damage was observed to occur on B737 aircraft departing Denver, Colorado between 5:00 and 8:00 p.m. Mountain Daylight Time (MDT) on 31 October (1 November, 0000–0300 UTC). The Denver METAR data during the period of interest (Table 1) have the initial weather condition as mist (BR) during the first hour of the event (0015 UTC), changing to −SN BR for the last three hours (0017–0353 UTC). Surface visibility during this time period ranged from 1.0 to 1.75 miles (the tower visibility was actually lower during this period due to the tower being in cloud at this time). The snow intensity is determined by the prevailing surface visibility [1], with *light* greater than or equal to 3/4 mile, *heavy* less than or equal to 1/4 mile, and *moderate* in between.

Winds during the period of engine damage were 5–7 knots out of the northeast, and as noted previously, the temperature was unusually cold at −8°C.

The noteworthy feature of Table 1 is the absence of reported freezing drizzle during the engine damage period. In the following we present evidence that significant ice accretion resulted from the presence of heavy freezing drizzle during this period. This conclusion is supported by an analysis of the synoptic weather pattern, upper air sounding, radar, satellite, and 1 min freezing rain sensor data.

Synoptic Weather Pattern

The engine damage at Denver occurred towards the end of a three-day arctic outbreak over the central U.S. A surface high-pressure region containing unseasonably cold, arctic air propagated southward from Canada and entered the northern portion of Colorado early on 29 October. Light snow fell at Denver on 29 and 30 October, producing a snow accumulation of 2 in. Temperatures during this period decreased to a low of −11°C on 30 October. Aircraft observations from the NCAR C-130 research aircraft on 29 October, 2100–2138 UTC at Jeffco Airport (50 miles west of Denver International Airport) show that freezing drizzle drops were also present in the arctic cloud at this time in addition to the snow observed at the surface (Fig. 3).

On 31 October, light snow occurred intermittently and temperatures increased slightly to −8°C. METARs from Denver during the late afternoon and evening on 31 October, when the engine damage occurred, are shown in Table 1. They show low clouds, reduced visibility, and light snow after 1 November, 0017 UTC, but there is no mention of any freezing precipitation. BR (mist)

Table 1 Denver METARs for the 31 October–1 November 2002 event

Denver METARs								
Date	UTC	Wind direction	Wind speed, kn	Surface Vsby, sm	WX	Sky cond	T, °C	Td °C
10/31	2253	020	09	1/2	−FZFG	OVC 001	−8	−9
10/31	2253	010	07	1 1/4	BR	BKN 001 OVC 003	−8	−9
11/01	0015	030	06	1 1/4	BR	SCT 001 OVC 003	−8	−9
11/01	0017	030	05	1 1/4	−SN BR	SCT 001 OVC 003	−8	−9
11/01	0035	040	05	1	−SN BR	SCT 001 OVC 003	−8	−9
11/01	0053	020	05	1	−SN BR	SCT 02 OVC 003	−8	−9
11/01	0153	010	05	1 1/2	−SN BR	SCT 002 OVC 004	−8	−9
11/01	0253	050	07	1 1/2	−SN BR	FEW 002 OVC 004	−8	−9
11/01	0353	050	07	1 3/4	−SN BR	OVC 004	−8	−9

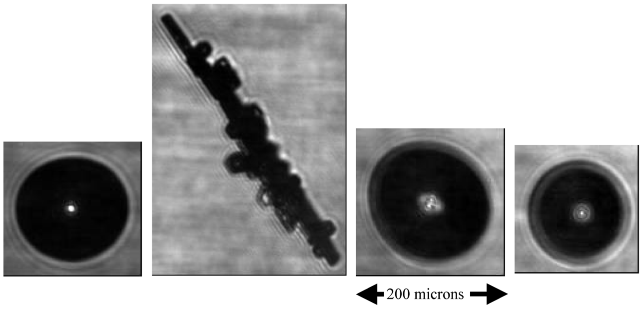

Fig. 3 Images of freezing drizzle and ice crystals from the Cloud Particle Imaging probe onboard the NCAR C-130 research aircraft at 2100 UTC 29 October 2002 from a cloud over Jeffco Airport, Colorado.

is automatically reported whenever the prevailing visibility is between 5/8 and 6 statute mile (SM), whereas fog is reported when the visibility falls below 5/8 SM [1]. When temperatures are below 0°C, fog is automatically reported as freezing fog (FZFG). Note that there is no provision in the Aviation Routine Weather Report [METAR (Fr)]/[Special Meteorological Aeronautical Report (Fr)] SPECI code for an observer to report freezing mist (FZBR) and thereby alert users to potential icing conditions.

Arctic air masses often contain freezing drizzle [2,3], due to the relatively warm in-cloud temperatures (> − 12°C), and the relatively clean air mass. At these relatively warm temperatures, ice crystal formation processes are often absent or weak. The relatively clean air mass allows drizzle processes to proceed rapidly [2,4] due to the low number of cloud droplets forming and weak depletion of water content and drizzle drops by ice crystal processes [5]. However, freezing drizzle is also commonly observed in the presence of low concentrations of ice [2], typically <0.1 ice particles/liter.

Upper Air Sounding Data

A skew-T/log P plot of the Denver 1 November, 00 UTC upper air balloon sounding, released during the period of engine damage, is shown in Fig. 4. It shows that the low-level cold air mass was saturated throughout, and was capped by a strong temperature inversion at about 720 hPa. The coldest temperature in this air mass was −11°C. This type of sounding is typical of freezing drizzle

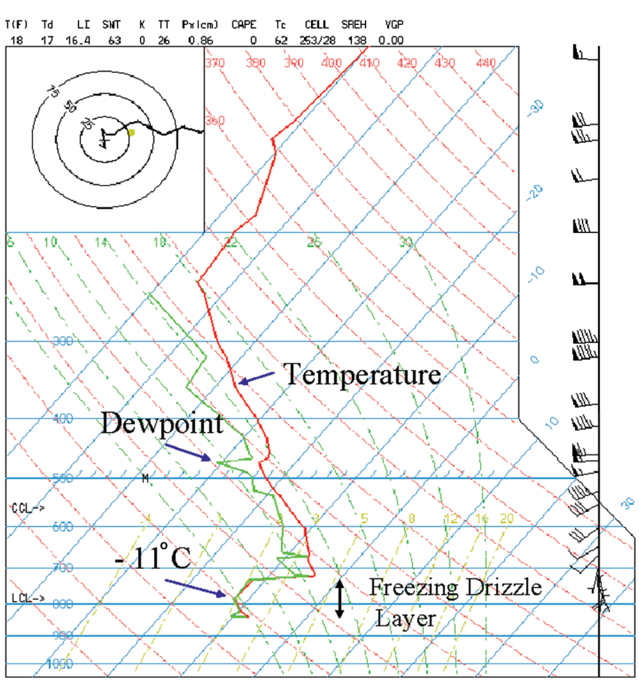

Fig. 4 Denver upper air sounding from 0000 UTC, 1 November 2002.

conditions produced by frontal overrunning in arctic air masses [2,3], as discussed in the preceding section. The key to the formation of freezing drizzle is the relatively warm cloud-top temperature, which leads to the production of relatively few ice crystals that could deplete the drizzle drops. Above the inversion the air is just below saturation, and at certain locations is likely ice saturated. These pockets of ice saturation likely produced a few ice crystals that fell into the lower cloud and produced the observed light snow conditions.

Radar Data

The radar return from freezing drizzle is typically between −10 and 0 dBZ due to the relatively small sizes of the drops (typically less than 0.5 mm in diameter). Snow, on the other hand, typically can have much larger radar reflectivity values (typical maximum values are 5–30 dBZ) due to the presence of snowflake sizes up to a centimeter in diameter. The radar reflectivity from the 0.5 deg lowest level scan from the NexRad Denver radar during the engine damage period is shown in Fig. 5. Two distinct features are evident in the image. Near Denver International Airport (DIA), there is a circular reflectivity pattern that is between −10 and 0 dBZ in intensity with a fairly uniform horizontal pattern. This type of echo pattern is consistent with either freezing drizzle or light snow [6]. The METAR reports at LIMON (to the southeast of DIA) and Arapahoe (to the southwest of DIA) both indicate the presence of freezing drizzle (LIMON actually is reporting freezing rain, which can occur when the intensity of freezing drizzle is high) beneath the uniform radar reflectivity pattern, suggesting that the echo was produced primarily by drizzle drops.

To the north of DIA, the reflectivity is significantly higher in intensity (up to 25 dBZ), and banded in nature, consistent with the presence of snow bands.

Satellite Data

The infrared satellite image shows the presence of relatively warm cloud-top temperatures near −12°C during the engine damage period (Fig. 6) similar to what the sounding data suggested. The region to the north of Denver where the radar suggested the presence of snow has a cloud-top temperature near −30°C, and thus large numbers of ice particles are expected to be present, consistent with the higher levels of radar return.

Freezing Rain Sensor Data

The recent deployment by the National Weather Service of more than 600 Goodrich Sensor Systems 872C3 freezing rain sensors (Fig. 7) at automated surface observing system (ASOS) sites has enabled the reporting of freezing rain on METARs using an algorithm that uses 1 min raw data from the sensor [7] in combination

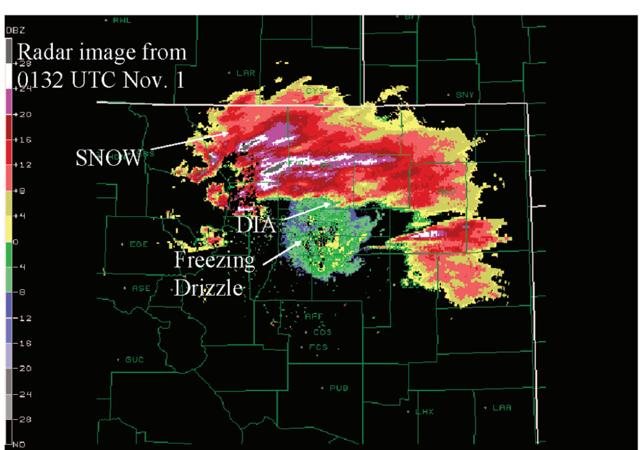

Fig. 5 Low-level (0.5 deg tilt) Denver NexRad radar image of radar reflectivity from 0132 UTC, 1 November 2002. Scale (in dBZ) is on the left side of the figure.

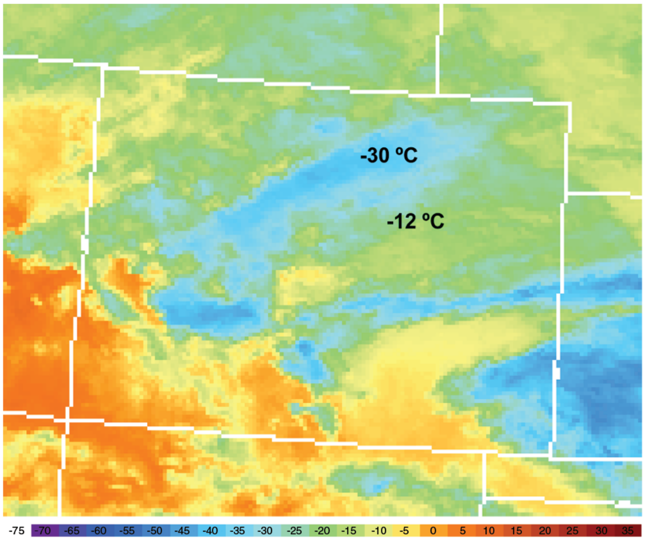

Fig. 6 Infrared satellite image of the cloud field over Colorado on 1 November, 0045 UTC. Cloud-top temperature is indicated by the color scale on the bottom of the figure. The upper cloud north of Denver is indicated by the location of the −30°C annotation in the figure and the location of Denver International Airport by the −12°C annotation, which is also the approximate cloud-top temperature.

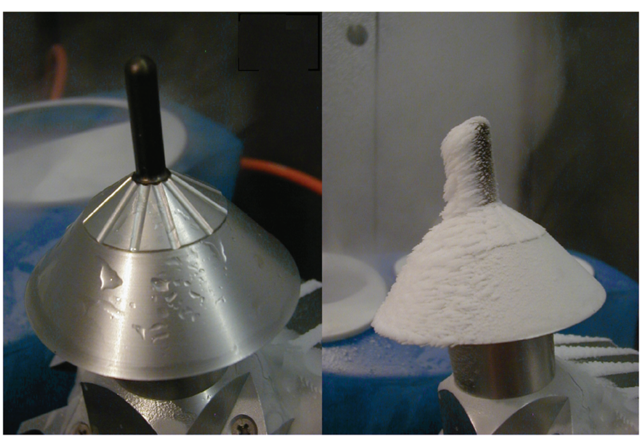

Fig. 7 Photograph of the Goodrich Sensor Systems 872C3 freezing rain sensor head. a) Clean sensor after a deicing cycle, b) iced up sensor. Black rod vibrates at 40,000 Hz without any ice buildup. Frequency decreases with the buildup of ice.

with other sensor data (Table 2). The NWS freezing rain algorithm [7] was expanded in the late 1990s to incorporate the identification of freezing drizzle [8,9]. The expanded algorithm, however, has not been operationally implemented into ASOS systems as of the writing of this article. The algorithms for freezing rain (currently operational on ASOS), freezing drizzle, and frost are shown in Table 2; the freezing drizzle algorithm was derived from two years of comparison of freezing rain sensors to manual observations of freezing drizzle occurrence, freezing drizzle intensity, and ice-accretion rates.

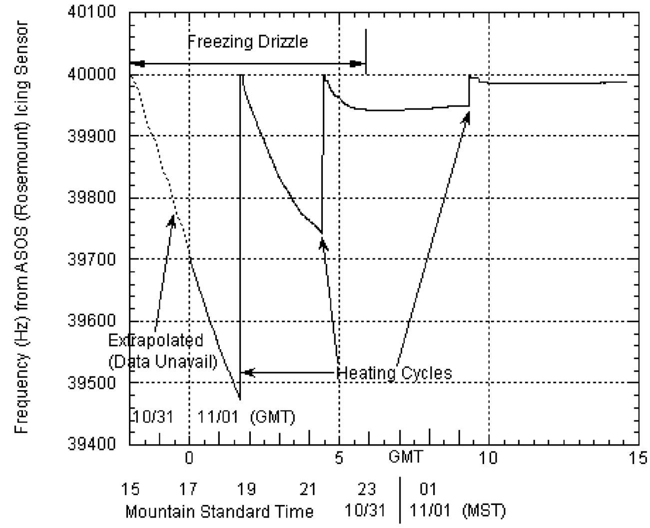

Fig. 8 Time series of the freezing rain sensor frequency for 31 October 2002.

As mentioned, these algorithms are designed to be used with raw, 1-min data from the ASOS. NCAR was archiving the raw 1-min Denver ASOS data from this case as part of its ongoing research and development regarding ground deicing issues under funding from the FAA Aviation Weather Research Program (AWRP). These data will be used in the following to diagnose the presence and intensity of freezing drizzle.

The raw output from the freezing rain sensor is the vibration frequency of the sensing rod. When no ice accretes on the rod the vibration frequency of the rod is approximately 40,000 Hz. When ice accretes on the rod, the frequency drops in proportion to the mass of the ice accretion. This information is used by the current ASOS system to indicate the presence of freezing rain using the algorithm described in Table 2. High values of mass accretion are related to the presence of freezing rain, whereas lower rates of accretion are correlated with the presence of freezing drizzle [8–10] (Table 2). Freezing drizzle is reported if: 1) the frequency is less than 39,967 Hz and the accretion rate on the sensor produces a frequency drop greater than 6 Hz in 15 min; 2) the light-emitting diode weather identifier (LEDWI) present weather sensor reports "no precipitation"; 3) the ambient temperature is less than or equal to 0°C; and 4) sky cover is overcast. All of these criteria were met during the engine damage period. The time series of frequency during this period (Fig. 8) shows a dramatic decrease in frequency during the engine damage period; this time series is a typical signature of ice accretion from freezing drizzle. The rapid increase of frequency observed in this plot is due to heating cycles of the instrument required to remove the ice. Ramsay [10] developed a method to determine freezing drizzle intensity (actually, ice-accretion rate) using the rate of frequency drop from the freezing rain sensor (Table 3). The frequency drop during the engine damage period was approximately 12 Hz per 5 min (Fig. 9), or 37 Hz per 15 min, indicating that the drizzle intensity was >0.02 in/h, equivalent to heavy drizzle intensity (Table 3). Figure 10 compares the drizzle algorithm to the LEDWI precipitation type and intensity algorithm that is currently used on ASOS. The thick bars are the freezing drizzle algorithm and the thin bars are from the LEDWI. Both the LEDWI and the drizzle algorithm reported no precipitation

Table 2 Ramsay algorithm for FZRA/FZDZ/FROST/SNOW

Ice detector	LEDWI present Wx type	Temp	Visibility	Sky cover	Present weather reported
Accretion frequency <39,967 Hz	RA, UP	<2.8 °C (<37°F)	Any	Any	FZRA
and 15 min accretion rate >13 Hz in 15 min	SN	Any	Any	Any	SN
Accretion frequency <39,967 Hz and 15 min	No precip	≤ 0 °C (<32°F)	Any	OVC	FZDZ
accretion rate >6 Hz in 15 min				Not OVC	None
Accretion frequency <39,967 Hz	No precip	≤ 0 °C (<32°F)	≥ 7 miles	CLR or SCT	FROST

Table 3 Freezing drizzle intensity based on a conversion of the Goodrich icing sensor frequency drop to accretion rate from [10]

Icing rates, generally based on rate per 15 min, .01 in/h = 66 Hz/h = 16.5 Hz/15 min

	FZFG	.001–.004 in/h	1–5 Hz/15 min
Light	−FZDZ	.004–.01 in/h	6–16 Hz/15 min
MDT	FZDZ	.01–.02 in/h	17–33 Hz/15 min
Heavy	+FZDZ	>.02 in/h	>33 Hz/15 min

from 1500–2000 UTC, 31 October. The ASOS algorithm using LEDWI and the freezing rain sensor are only designed to report rain, freezing rain, or snow precipitation types and their intensity, and therefore do not automatically report freezing drizzle.

This figure indicates that the drizzle algorithm would have reported heavy freezing drizzle during the engine damage period (00–03 UTC) instead of the light snow reported by the observer. The LEDWI instrument reported ?0 or ?1, which indicates that the sensor detected precipitation, but did not have sufficient signal to determine the type or intensity.

Note that the ASOS LEDWI instrument did not report snow until the end of the engine damage period (0400 UTC) when the heavy snow band shown in Fig. 5 moved into the area from the north. Thus the light snow report on the METARs during the engine damage period was generated manually by the observer overriding the automatic ASOS precipitation type algorithm, which would have reported unknown precipitation based on the 1 min LEDWI data.

Note that drizzle intensity by a manual observer is determined by visibility. Because visibility is currently required to be used to determine drizzle intensity; only light drizzle would have been reported in this case compared to the heavy drizzle intensity derived from the freezing rain sensor using the drizzle algorithm. Thus, the determination of drizzle intensity from visibility suffers from the same ambiguity as the determination of snow intensity using visibility [11]. This issue is discussed further in a following section.

Discussion of the 31 October 2002 Event

The preceding analysis of the synoptic, sounding, radar, satellite, and 1-min freezing rain sensor data are all consistent with the presence of moderate to heavy freezing drizzle during the engine damage period, suggesting that this was the most likely weather phenomenon occurring during this event. After the B737 aircraft were deiced at the gate on Concourse B they most likely ingested freezing drizzle into the engines as the engines operated at idle speeds. The aircraft taxied to the deicing pad located just west of Concourse B for deicing, and were deiced with engines running, still

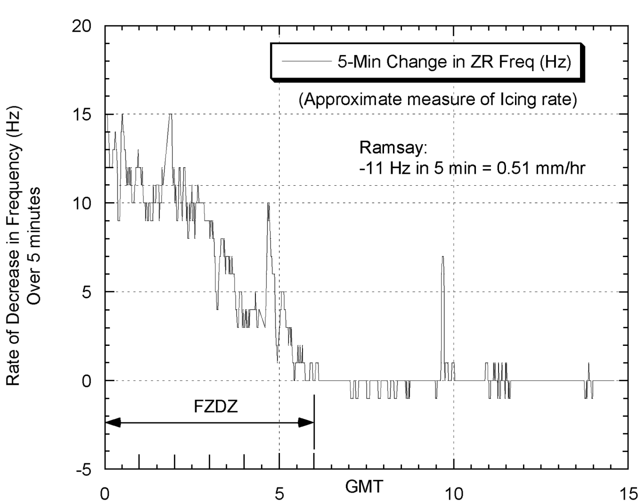

Fig. 9 Time series of rate of frequency decrease over 5 min from the Goodrich sensor on 1 November, 0–15 UTC. The positive values between 0 and 6 UTC corresponds to the presence of freezing drizzle.

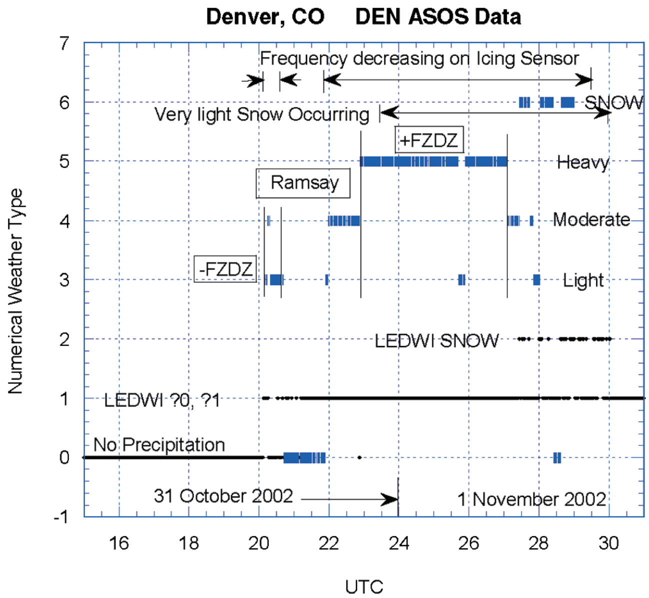

Fig. 10 Time series of numerical weather type between 31 October 2002, 1500 UTC and 1 November 2002, 0700 UTC. Thin solid line indicates LEDWI observations, thick solid line indicates Ramsay algorithm reports of light, moderate, or heavy freezing drizzle, snow, or no precipitation.

at idle speeds. Because the engines continued to run, freezing drizzle was ingested during the deicing process. After deicing, the aircraft taxied to the takeoff runway. Taxi times from the gate to takeoff during this event were between 25 and 50 min, with an average of 30 min. Thus, the aircraft had ample time to ingest significant amounts of freezing drizzle. If United Airlines staff had known that moderate to heavy freezing drizzle conditions existed, they would have implemented engine run-ups every 30 min as per Boeing Aircraft guidelines and United Airlines policy for freezing precipitation conditions to shed any accreted ice before the buildup became large enough to cause damage (since this incident United Airlines has increased engine run-ups to every 10 min during moderate to heavy freezing drizzle conditions). Just before takeoff the engines are typically run-up to 70% N1 to shed ice. Any accreted ice will likely be shed during this time or during the takeoff. The ingest of this shed ice into the engines was the most likely cause for the engine damage that occurred. A few United Airlines pilots from the damaged aircraft reported vibrations during takeoff or shortly thereafter, consistent with this scenario. Thus, a weather report that indicated the presence of heavy freezing drizzle may have averted these incidents.

An interesting aspect of this event was that only the right engines were damaged. We speculate that because the winds were from the northeast, the left side engine may have been shielded from the wind-driven drizzle by the fuselage during the taxi to the deice pad and takeoff runway located to the west of the gates.

Comparison to a Braathens Incident on 7 February 2003

A similar incident of B737 jet engine damage occurred in Oslo, Norway Gardermoen Airport on 7 February 2003 between 1614 and 1816 UTC. During this time light freezing drizzle was reported with an ambient temperature near −7°C. However, evidence from roadways and the tarmac reported by SAS and Braathens staff were that heavy freezing drizzle was actually occurring. We suspect that this was a case of high visibility and high freezing drizzle rate, which Ramsay [10] has shown can occur nearly 50% of the time. Figure 11 is derived from data collected by Ramsay and shows the percent of time that the ice-accretion rate during freezing drizzle is correctly represented by visibility-based drizzle intensity as opposed to using the algorithm shown in Tables 2 and 3. As shown, nearly all drizzle intensity reports by visibility (96%) fall into the light category as in

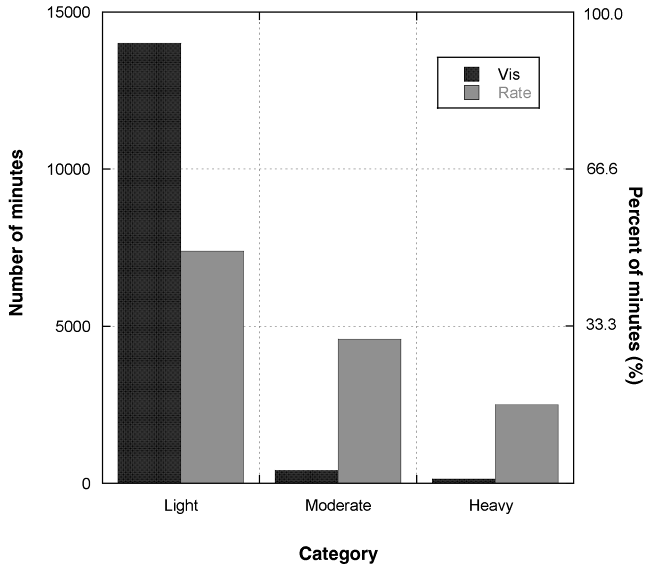

Fig. 11 Histogram of drizzle frequency for light, moderate, and heavy drizzle intensities defined by visibility and mass accumulation rate using observational data collected by Ramsay [10].

this event, whereas in reality only 54% should be in this category with the remaining 46% in the moderate to heavy category.

The engine damage for the Braathens case occurred for only the B737-300 engines. The damage was to the tips of the fan blades, similar to the United engine damage (see Fig. 1) and also to the HPC blades. Freezing drizzle is a common occurrence at the new Gardermoen Airport due to its location in a valley 40 miles to the north of the city of Oslo. Thus, engine icing due to drizzle ingest is fairly common. As a result, a special heated air blower and special front engine covers with a connection for the heater hose has been developed for removing engine ice at the gate during this type of condition (the heater blower was developed by SAS and the engine covers in cooperation between Braathens and SAS). During the event of 7 February 2003, the engines were deiced at the gate using this blower system, but again experienced ice buildup during the taxi to the deicing pad and to the takeoff runway. Deicing occurred with the engines running as in the United case and the taxi times averaged between 23 and 50 min, very similar to the United times. Braathens pilots ran up their engines to 70% N1 at the head of the takeoff runway. Three of the six aircraft experienced higher than normal vibrations at this time. The crew continued the engine run-up until the vibration was reduced to normal levels and the aircraft took off. Six Braathens B737 aircraft engines were damaged in this fashion during this event. Once Braathens was aware of the damage they stopped operations at Gardermoen Airport at 2145 UTC, 7 February.

Braathens engineers believe that the engine damage occurred due to the liberation of ice from the back side of the fan blades during engine run-up. Ice, so liberated, is centrifuged to the outer portions of the engine where it can damage the blade tips when ingested into the engine. United engineers also suggested the same scenario for their engine damage.

Thus, the two jet engine damage cases were nearly identical in terms of temperature (cold, near −7°C), the presence of heavy freezing drizzle and high visibility, the type of damage incurred to the engine fan blades and the type of aircraft engine damaged (B737-300s), and time of taxi. Both cases also had reported weather that, although technically correct, did not alert operators to the existence of hazardous icing conditions, and resulted in nonaction by both the aircraft crew regarding the implementation of more frequent engine ice shedding procedures, and other responsible personnel to stop the operations.

Engine Damage During a Warmer Freezing Drizzle Case at Denver

On 30–31 October 2003, another freezing drizzle event occurred at Denver International Airport, *exactly* one year from the date of the first event described. Six B737-300 engines were damaged during this event, with similar damage to the previous year. The METAR was of light freezing drizzle during the engine damage period, whereas the actual ice-accretion rate was again equivalent to moderate to heavy freezing drizzle based on the freezing drizzle algorithm (Figs. 12 and 13), radar data (reflectivity between 0 and −10 dBZ with a cloud top of 3 km, typical of freezing drizzle conditions in the Denver area) and sounding data (cloud-top temperature of −11°C with dry air above the cloud top).

Photographs of the actual ice accretion on the spinner and fan blades during this event are shown in Fig. 14. Note the formation of

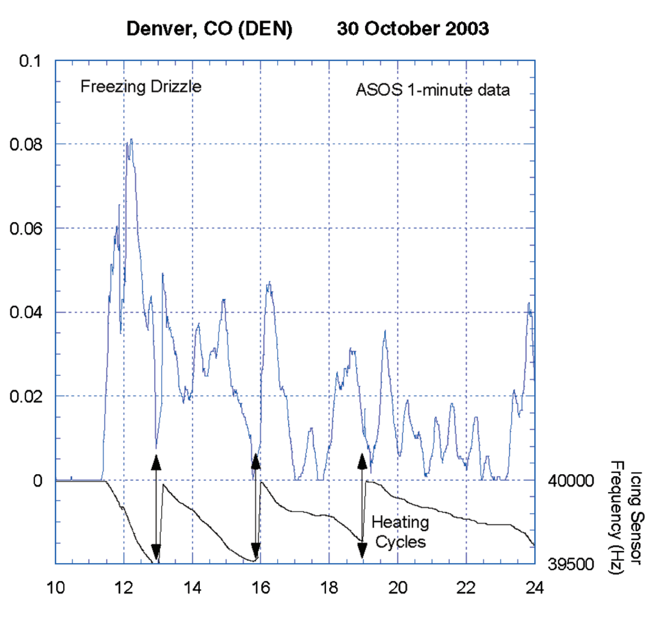

Fig. 12 Time series of icing sensor frequency and ice accretion rate, 30 October 2003.

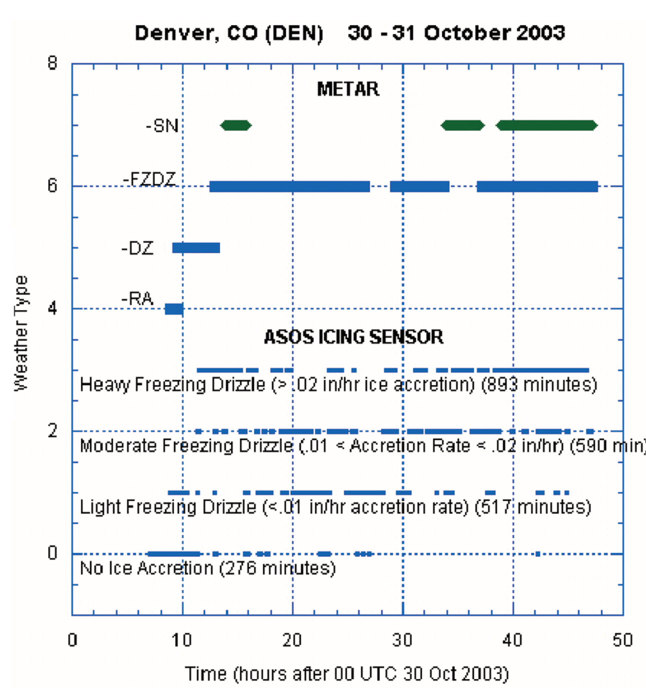

Fig. 13 Time series of freezing drizzle rate based on the Goodrich icing sensor with the Ramsay algorithm applied (thin lines), and the METAR observations (thick lines) between 30 October 2003, 0000 UTC and 1 November 2003 0200 UTC.

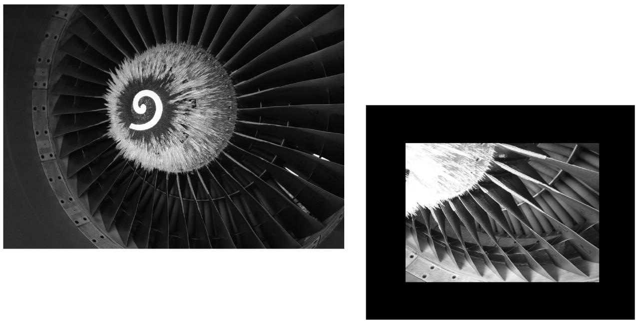

Fig. 14 Photograph of ice accretion on spinner and fan blades, 30 October 2003.

ice spikes on the spinner, which could easily shed during takeoff rotation. The temperature at the surface during this event, however, was −3°C, significantly warmer than the 31 October 2002 event and the Gardermoen Airport events, which occurred near −8°C. Thus, engine damage is not only limited to the cold freezing drizzle events.

Following this event, United Airlines staff conducted tests of the ice accretion into engines during a freezing fog event on 6 November. The results showed rapid accretion of ice on both the spinner and on the sides of the engine blades (Fig. 15). However, no ice spikes formed in this case. 1/4 in of ice was observed to build up on the blades within 15 min of taxi, and 1/2 in of ice within 30 min of taxi. Ice accretions were observed to occur on a variety of jet engine types, not just the B737s. Thus, taxi during freezing fog may also be of concern. More research is needed to verify this suggestion.

Factors Leading to the Misreporting of Drizzle Intensity

In this section we explore reasons for the wide variability in drizzle rate for a given visibility. Three areas will be examined: 1) the physics of visibility degradation due to drizzle drops, 2) factors impacting an observer's estimate of visibility during drizzle conditions, and 3) the impact of day and night observing conditions.

Physics of Visibility Degradation Due to Drizzle Drops

Drizzle drops are between 0.2 and 0.5 mm in diameter and are essentially spherical. Thus, variations in visibility due to shape variations that occur for snow [11] are not likely important. Observations suggest, however, that the size distribution of drizzle can vary significantly from storm to storm and even within a given storm [12]. Drizzle size distributions as measured by research aircraft typically show an exponential size distribution shape [2,12], although gamma size distributions are also observed. The equation for an exponential size distribution is given by:

$$N(D) = N_o \exp(-\Lambda D) \tag{1}$$

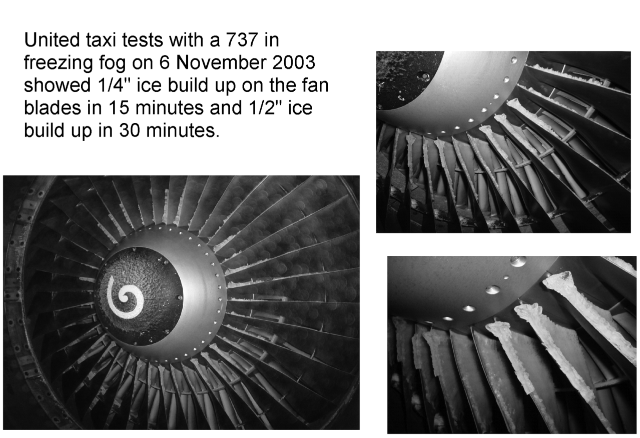

Fig. 15 Ice accumulation on spinner and fan blades during Denver freezing fog event.

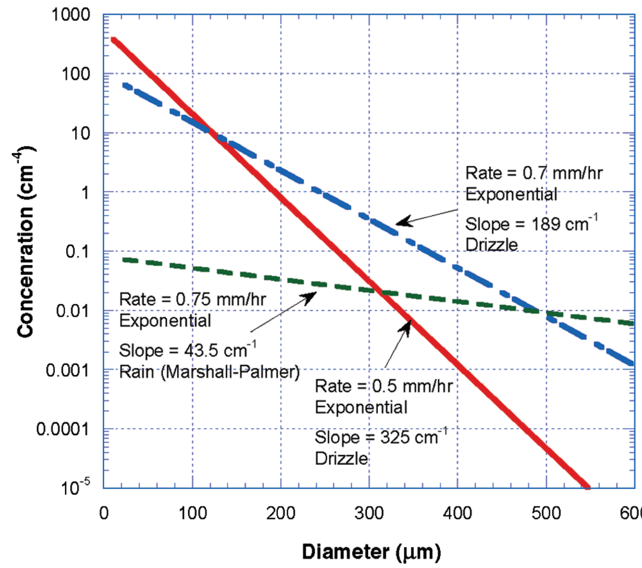

Fig. 16 Drizzle drop concentration as a function of diameter assuming an exponential size distribution for two drizzle drop size distributions and one rain distribution. Rates (mm/h) are indicated, as well as slopes of the distribution.

where D is the drizzle drop diameter, Λ the slope of the size distribution, N_o the y-intercept and $N(D)$ the number of drops per diameter size interval. Typical drizzle size distributions are shown in Fig. 16 for moderate to heavy drizzle rates (0.5–0.75 mm/h). A raindrop distribution at a rate of 0.75 mm/h is shown for comparison.

The equation relating visibility (km) during drizzle conditions to drizzle rate (mm/h) can be derived using the method described by Rasmussen et al. [11] for the exponential drizzle size distribution shown in Eq. (1) assuming a fallspeed relationship for drizzle drops given by

$$V_t = 3750D \tag{2}$$

where V_t is the drizzle drop terminal velocity in cm/s and D is drizzle drop diameter in cm. The equation relating visibility to drizzle rate is then given by

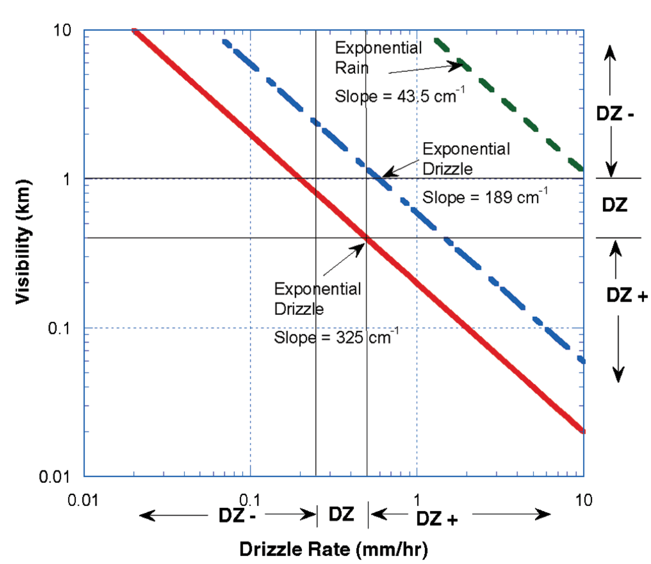

Fig. 17 Visibility vs drizzle rate based on Eq. (3) for an exponential drizzle drop size distribution with the slopes given in Fig. 16. Also indicated on the y- and x-axes are the definition of drizzle intensity based on visibility and rate, respectively.

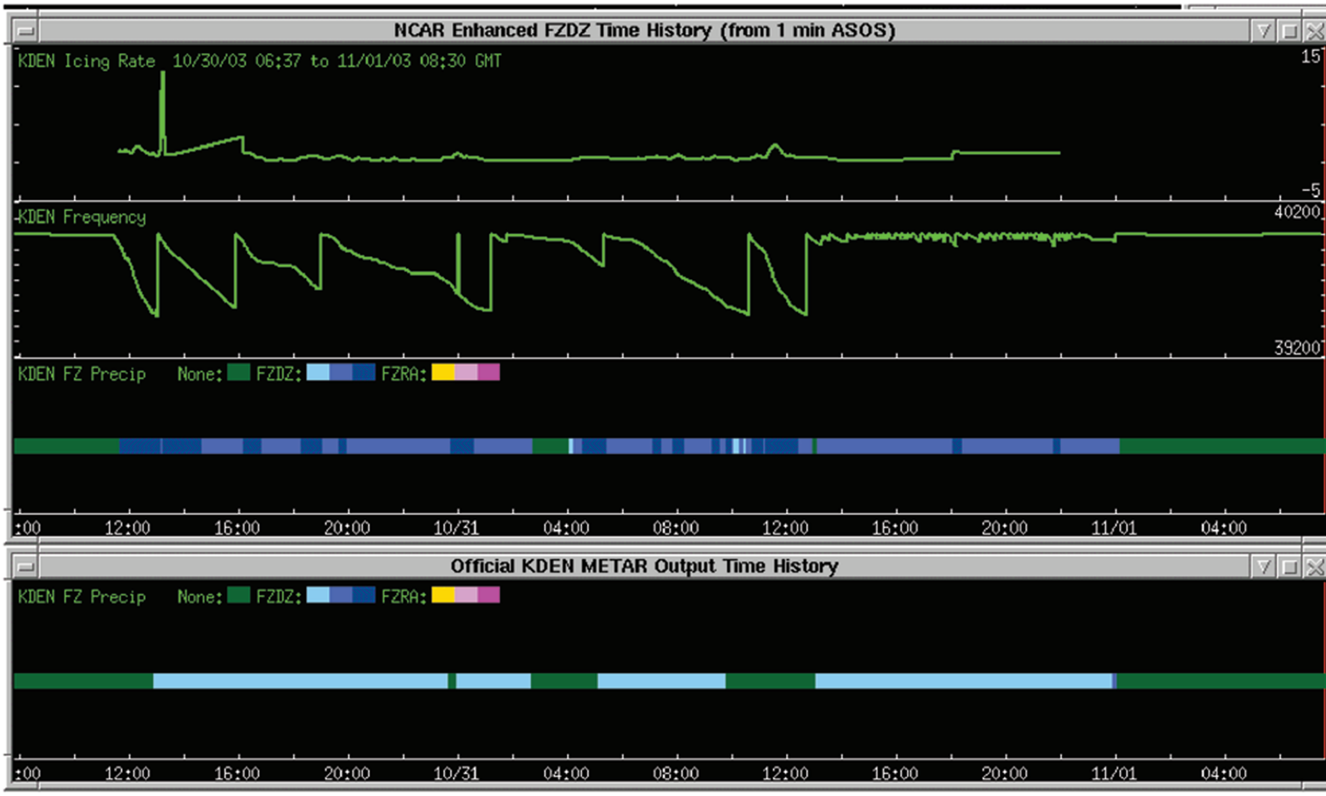

Fig. 18 Graphical depiction on the Weather Support to Decision Making (WSDM) system of freezing drizzle intensity by mass rate (light, moderate, and heavy) for the 30 October 2003 event. Upper panel is the icing rate and frequency from the Goodrich sensor, the middle panel is the color-coded freezing drizzle intensity from the Ramsay algorithm, and the bottom panel is the METAR reports for this day.

$$\text{Vis (km)} = 1760\rho_w\Gamma(5)/[\text{Rate(mm/h)}\Gamma(3)\Lambda^2] \tag{3}$$

This equation shows that there is an inverse relationship between visibility and drizzle rate, with the constant of proportionality varying only as a result of variations in the slope of the exponential size distribution, Λ. Figure 17 provides a plot of this equation using the slope of the drizzle and rain size distributions shown in Fig. 16. Variations in rate in Fig. 17 for a given curve are thus only due to variations in the y-intercept parameter N_o [Eq. (1)]. Also shown in Fig. 17 just outside the x- and y-axis labels are the definitions of light, moderate, and heavy drizzle on a visibility basis (y-axis) and mass basis (x-axis). The drizzle curve with a slope of 325 cm^{-1} represents the exponential drizzle size distribution slope that results in a consistent definition of drizzle rate on a visibility and mass basis. Typical drizzle size distributions, however, show shallower slopes than this hypothetical distribution. The curve in Fig. 17 with a slope of 189 cm^{-1} is one such example that was observed during a winter

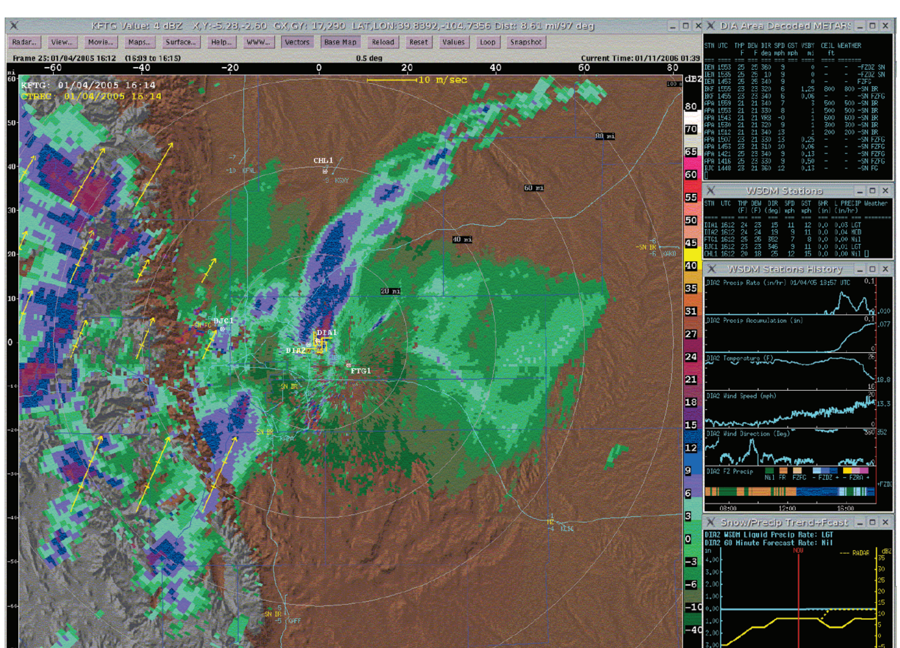

Fig. 19 WSDDM system graphical display.

storm [2], and also produced by a detailed numerical model [12]. Because visibility reduction is proportional to the sum of the drop surface areas, distributions with more large drops and fewer small drops (as this distribution does as compared with the distribution with a slope of 325 cm^{-1}, see Fig. 16) will have higher visibilities. As a result, the visibility for a given drizzle rate will be higher, the shallower the slope. The consequence of this is an underestimate of drizzle rate by visibility. For example, a rate of 0.6 mm/h, which is heavy on a mass basis and also on a visibility basis if the curve with a slope of 325 cm^{-1} is used, is estimated to be of only light intensity based on visibility using the curve with a slope of 189 cm^{-1}. The rain curve in Figs. 16 and 17 shows that as drizzle moves into raindrop sizes the visibility will be quite high as the high concentration of small drops with high total surface area is converted to fewer large drops with a lower total surface area.

If most drizzle drop size distributions have a slope shallower than 325 cm^{-1}, then most of the reported drizzle intensities based on visibility will be reported as lighter than the actual mass based rate as observed in the Ramsay studies (Fig. 11). Further observational data on drizzle drop size distributions, especially at the ground, will be needed to confirm this suggestion.

Factors Impacting the Observation of Visibility During Drizzle Conditions

Observations show significant time and space variation of drizzle rate [13]. Because an observer's estimate of visibility during drizzle is taken at a specific time (observation time) and over a distance (typically how far he/she can see to known reference points), there will be a natural variability in the drizzle rate estimated independent of changes in the drizzle size distribution. Changes in lighting conditions can also have an impact.

Impact of Day vs Night Observing Conditions

The visibility during drizzle conditions is a factor of 2 higher during the night than during the day due to the sun being the predominant light source during the day and artificial lighting being the dominant light source at night [11]. As a result, estimates of drizzle intensity at night will be lower than those during the day for the same mass accumulation rate. The estimate of drizzle intensity during both of the Denver cases were likely affected by this behavior, leading to lighter drizzle intensity estimates by the observer than what was actually occurring. The factor of 2 change in visibility from day to night results in a rate of heavy during the day going to moderate at night, and a moderate intensity during the day going to light during the night.

Thus, the variability in drizzle size distribution, spatial and temporal variations in the pattern of drizzle intensity, and whether it is day or night help explain the lower drizzle intensity estimated on a visibility basis as compared with a mass based intensity as observed by Ramsey [10] (Fig. 11). Thus, the use of visibility to estimate drizzle rate is problematic and should be avoided, especially for ground deicing purposes, because it can lead to serious engine damage if underestimated. Instead of using visibility, drizzle rate should be directly measured on a mass rate accumulation basis using a sensitive precipitation gauge, Goodrich freezing rain sensor, or similar device.

Demonstration of a Real-Time Freezing Drizzle Warning System

Current reporting of freezing drizzle by the National Weather Service is performed by an observer estimating freezing drizzle intensity by visibility. This is reported on METARs and ATIS hourly, or more frequently if conditions are changing (so-called specials or SPECI). This paper has shown, however, that aviation users need freezing drizzle reports based on a mass accumulation basis and updated at least every 5 min (engine damage occurred in as little as 15 min exposure times). A demonstration of a real-time freezing drizzle warning system based on the preceding algorithm was conducted during the winter of 2004/2005 at Denver International Airport. The freezing drizzle algorithm was implemented into the Weather Support to Deicing Decision Making (WSDDM) real-time winter weather nowcasting system [14]. The system provides real-time weather updates at airport locations experiencing winter weather conditions, including a one-hour snowfall rate forecast, and is currently operational at Denver International and Minneapolis/St. Paul Airports. A graphical depiction of the current precipitation type and rate from the freezing drizzle algorithm was developed as a time series (Fig. 18) and added to the WSDDM system display (Fig. 19). The new graphic provides an accurate estimate of the actual freezing precipitation type (freezing rain or freezing drizzle) and precipitation intensity every minute based on a mass rate of ice accumulation instead of visibility.

United Airlines staff meteorologists used this system during the winter of 2004/2005 to alert pilots via NOTAMS on the presence of freezing drizzle in Denver. Eight freezing drizzle events were identified by the system, and appropriate NOTAMS filed. Based on the NOTAMS, pilots implemented engine run-ups every 10 min during these events to shed any accreted ice, with the result that no engine damage occurred during this winter.

Conclusions

The main conclusions from this study are as follows:

1) A serious ground icing hazard has been identified involving the accretion of ice from heavy freezing drizzle onto jet engine fan blades and spinners and subsequent shedding during takeoff leading to bent fan blades and other possible damage.

Three cases of engine damage were reported in this study for which heavy drizzle was misreported as either light snow or light freezing drizzle. If operators can be alerted to significant icing conditions by the reporting of heavy freezing drizzle on a mass accumulation basis, this hazard may be avoided if frequent engine run-ups are performed. The ice-accretion rates during the three cases of engine damage presented in this paper were estimated to be equivalent to those that occur in heavy freezing drizzle rates. This hazard occurred at a variety of temperatures (-3 to $-8°C$), indicating that it is not only a cold temperature phenomenon. Fan blade damage has certainly occurred in the past; however, the cause of the damage was in many cases not readily apparent. This study identifies one of those causes as being accretion of ice from heavy freezing drizzle during taxi of jet engine aircraft on the ground.

2) The current method to report freezing drizzle intensity based on METAR/SPECI using visibility results in underreporting ice-accretion rates in freezing drizzle 50% of the time.

Engine run-ups are typically only required if the freezing drizzle intensity is reported as moderate to heavy. Theoretical considerations and observations [13] showed that a likely cause of the lower estimate of drizzle rate by visibility is the variation in the drizzle drop size distribution, spatial and temporal variations in drizzle rate, and the higher visibility at night during drizzle conditions (leading to moderate drizzle going to light, and heavy drizzle to moderate when going from day to night).

Thus, future weather warning systems should rely on drizzle rates determined on a mass basis, such as the Ramsay algorithm applied to the 1-min freezing rain sensor data. This freezing drizzle algorithm has been implemented into the WSDDM winter weather nowcasting system [14] which provides warning of heavy freezing drizzle conditions every minute based on the ASOS Goodrich Sensor Systems 872C3 freezing rain sensor.

3) Freezing drizzle can occur during very light snow conditions, and may be reported only as light snow due to the difficulty of observing drizzle at the same time as light snow.

Light snow is usually observable by the naked eye (opaque, white particle), whereas drizzle is often not (clear, small drop less than 0.5 mm that is typically smaller than snow particles).

4) Current automated weather systems (such as ASOS) that are not augmented by an observer do not have the capability to report freezing drizzle, and therefore pilots need to be especially attentive to the presence of freezing drizzle at airports without augmentation of the official observation.

Drizzle consists of small droplets that appear to move with the air currents and are readily apparent on a windshield as small droplets (0.1–0.5 mm in diameter) of high concentration.

5) Real-time observations of freezing drizzle (updated at least every 5 min) are needed at airports to avoid this hazard in the future.

The main solution to the icing problem presented in this paper is the accurate and timely reporting of the correct "precipitation" type and intensity based on liquid equivalent rate. This will allow pilots to implement engine run-up procedures that can shed any accreted ice before it becomes hazardous. This solution was tested at Denver International Airport during the winter of 2004/2005 and successfully averted engine damage during eight freezing drizzle events.

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