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

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1. INTRODUCTION

On Oct. 31, 2002, twelve United Airlines 737 aircraft incurred jet engine damage after experiencing 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 (figure 1, photo of bent fan blades) . Total damage was reported by United Airlines as being over $2 million dollars, with one engine requiring replacement. The damage was noted after the aircraft landed at their destination airports. The aircraft that incurred damage departed Denver between 5:00 and 8:00 p.m. Mountain Standard Time (MST). The weather observer at Denver reported mist and light snow during this time period, and also unseasonably cold temperatures (-8 C). While in-bound 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 build up that occurred via in-flight ice accretion. This 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), 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 that augmented the METAR in this case to report snow and mist.

One year later, on Oct. 31 2003, Denver again experience freezing drizzle during which additional jet engines were damages. Another similar case of engine damage occurred at Oslo Gardemoen airport in Norway with Braathens Airlines 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 period when the engine damage occurred in both cases was most likely heavy freezing drizzle rather than light snow and mist as reported in the Oct. 31, 2002 Denver case or light freezing drizzle as reported during the Oct. 31, 2003 Denver and February 2002 Oslo, Norway cases. If the flight crew had been aware of the heavy freezing drizzle conditions, standard engine run-up procedures would have been implemented to shed any potential ice accumulation. Since the official weather observations did not indicate heavy freezing drizzle, this procedure was not implemented, 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 damage reported to the aircraft.

Section 2 presents an analysis of the weather conditions associated with the Denver October 31, 2002 incident and section 3 an overall discussion of this event. Section 4 presents a comparison to the Denver October 31, 2003 case and the February 2002 Oslo, Norway event. A proposed solution to this problem is presented in section 5, with final conclusions in section 6.

2. ANALYSIS OF WEATHER CONDITIONS BETWEEN OCT. 31, 2300 UTC AND NOV. 1, 0400UTC, 2002

The METAR data during the period of interest (Table 1) has 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 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 (Federal Meteorological Handbook 1, 1995).

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 freezing drizzle during the engine

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damage period. In the following we present evidence that the main precipitation type was in fact heavy freezing drizzle during this time period based on an analysis of the synoptic weather pattern, upper air sounding data, radar data, satellite data, and one minute freezing rain sensor data.

2.1 Synoptic Weather Pattern

This event occurred towards the end of a three day arctic air outbreak over the central U.S. A surface high pressure region containing extremely cold arctic air propagated southward from Canada, entering the northeastern portion of Colorado near 0000 UTC on Oct. 29. Cold frontal passage occurred at Denver at 0300 UTC, Oct. 29, with winds shifting to northeasterly at 10 knots at this time. Light snow fell between 1000 UTC Oct. 29 and 2100 UTC Oct. 30, producing a snow accumulation of 2 inches. Temperatures continued to drop during this period, reaching a low of 12 F at 1400 UTC on Oct. 30. During the 31st, light snow occurred intermittently until 1400 UTC, and temperatures increased slightly to 18 F. The initial northeastearly flow gradually turned to weak easterly by 1400 UTC on the 30th, and remained weak easterly until 1700 UTC on the 31st when the winds turned northerly again and strengthened. Upper level forcing also became weaker after 1700 UTC on the 31st, reducing the production of snow in the upper level cloud to near zero. The combination of a shallow cold cloud with a top temperature of -11 C and upslope flow on the order of 5-7 knots from the northeast with weak upper level forcing provided ideal conditions for the formation of freezing drizzle in this cloud (Rasmussen et al. 1995).

2.2 Upper air sounding data

The 00 UTC Denver sounding shows that the cold air is about 1 km deep and saturated, indicating the presence of a shallow cloud as discussed above (Fig. 2). A strong inversion existed at the top of the cold air at 720 hPa, with the coldest temperature in the cloud layer being -11 C. This type of sounding is typical of freezing drizzle conditions produced by frontal overrunning (Rasmussen et al. 1995). Key to the formation of drizzle is the relatively warm cloud temperatures present. Above the inversion the air is just below saturation, and at certain locations likely ice saturated. These pockets of ice saturation likely produced the observed light snow conditions.

2.3 Radar data

The radar return from freezing drizzle is typically between -10 to 0 dBZ due to the relatively small sizes of the drops (typically less than 200 microns in diameter). Snow, on the other hand, typically can have much larger radar reflectivity values (typical maximum values are 25 to 30 dBZ), due to the presence of snowflake sizes up to a cm in diameter. The radar reflectivity from 0.5 degree lowest level scan from the NexRad Denver radar during the engine damage period is shown in figure 3. Two distinct features are evident in the image. Near Denver International airport, there is a circular reflectivity pattern that is between -10 and 0 dBZ in intensity with a fairly uniform horizontal pattern. To the north of Denver, the reflectivity is significantly higher in intensity (up to 25 dBZ), and banded in nature. The circular echo over DIA is consistent with either freezing drizzle or light snow (Ikeda and Rasmussen 2003). The echo to the north of DIA is consistent with snow bands. 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. Thus, the reported weather conditions beneath the uniform echo is freezing drizzle (or freezing rain) other than DIA.

2.4 Satellite Data

The infrared satellite image shows the presence of relatively warm cloud top temperatures near -10 C during the engine damage period (figure not shown). A number of recent studies have shown that one of the key factors allowing the presence of freezing drizzle is cloud top temperatures warmer than -12 C (Geresdi et al. 2003, Bernstein et al. 1997, Cober et al. 1996, Rasmussen et al. 1995). At colder temperatures sufficiently high concentrations of ice crystals will form that will deplete the supercooled cloud water and also freeze the drizzle drops. Thus, drizzle is typically suppressed at cloud top temperatures less than -12 C. Note, for instance, that the region to the north of Denver where snow is know to be present has cloud top temperatures near -30 C, and thus large numbers of ice particles are expected to be present, consistent with the higher levels of radar return.

2.5 One minute Freezing Rain Sensor Data

The recent deployment by the National Weather Service of freezing rain sensors (figure 4) provides an additional dataset that can be used to determine precipitation type based on algorithms developed by Ramsey 1999. The Ramsey algorithms for freezing rain, freezing drizzle, and frost are shown in table 2.

These algorithms are designed to be used with the raw ASOS data, and therefore require the use of the one minute raw ASOS data. Fortunately, NCAR was archiving the one minute 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). The raw output from the freezing rain sensor is a vibration frequency of the sensing rod. When no ice accretes on the rod the vibration frequency of the rod is approxiamately 40,000 Hz. When ice accretes on the rod, the frequency drops in proportion to the thickness of the ice accretion. This information is used by the current ASOS system to indicate the presence of freezing rain. Table 2 also gives an extension of the freezing rain algorithm by Ramsey (NWS 1999 report) to detect freezing drizzle using the one minute data from the freezing rain sensor and other relevant information from the ASOS system. 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 minutes, 2) the 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 are met during the engine damage period. Ramsey (1999) has also developed a method to determine freezing drizzle intensity using the rate of frequency drop from the freezing rain sensor (Table 3). The frequency drop during the engine damage period was 37 Hz per 15 minutes (figure 5), indicating that the drizzle intensity was > 0.02 in/hr, or heavy drizzle intensity. Figure 6 compares the Ramsey drizzle algorithm to the LEDWI precipitation type and intensity algorithm that is currently used on ASOS. The thick bars are the Ramsay algorithm and the thin bars are from the LEDWI. Both the LEDWI and the Ramsay algorithm reported no precipitation from 1500 – 2000 UTC, Nov. 1. Note that the ASOS algorithm using LEDWI and the freezing rain sensor is only designed to report rain, freezing rain, or snow precipitation types and their intensity, and therefore does not automatically report freezing drizzle. This figure indicates that the Ramsay algorithm would have reported heavy freezing drizzle during the engine damage period 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 neither the LEDWI or the Ramsay algorithm reported snow until the end of the engine damage period (0400 UTC) when the heavy snow band shown in figure 3 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 overiding the automatic ASOS precipitation type algorithm, which would have reported no precipitation based on the one minute LEDWI data.

Note that drizzle intensity by a manual observer is determined by visibility. If visibility were used to determine drizzle intensity in this case, only light drizzle would have been reported as compared to the heavy drizzle intensity derived from the freezing rain sensor using Al Ramsay's algorithm. Thus, the determination of drizzle intensity from visibility suffers from the same ambiguity that the determination of snow intensity using visibility does (Ramsey 1999, Rasmussen et al. 1999).

3. DISCUSSION OF THE OCT. 31, 2002 UNITED EVENT

The above analysis shows that the synoptic, sounding, radar, satellite, and one minute freezing rain sensor data are all consistent with the presence of heavy freezing drizzle during the engine damage period, indicating that this was the most likely weather phenomenon occurring during this event. Thus, after the aircraft were deiced at the gate on Concourse B they most likely ingested freezing drizzle at very cold temperatures into the engines 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 at idle speeds. Thus, the engines continued to ingest freezing drizzle during the deicing process. After deicing, the aircraft taxied to the takeoff runway. Average taxi times from gate to takeoff during this event were 25 – 50 minutes, with an average of 30 minutes. Thus, the aircraft had ample time to ingest significant amounts of freezing drizzle. If United had known that heavy freezing drizzle was occurring, they would have implemented engines run-ups every 30 minutes as per Boeing Aircraft guidelines and United policy to shed any accreted ice before the build up became large enough to cause damage. Just prior to takeoff the engines are typically run up to 70% N1 to shed any ice. Any accreted ice will likely be shed during this time or during the takeoff. This ingest of this shed ice into the engines was the mostly likely cause for the engine damage occurred. A few United pilots from the damaged aircraft reported vibrations during takeoff or shortly thereafter, consisten with this scenario.

Thus, a correct freezing drizzle report including intensity may have averted this incident.

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

4. COMPARISON TO A BRAATHENS AIRLINES INCIDENT ON FEB. 7, 2003.

A similar incident of jet engine damage occurred in Oslo, Norway Gardemoen airport on Feb. 7, 2003 between 1614 – 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 drizzle intensity, which Ramsey (1999) has shown occurs nearly 50% of the time. Figure 7 is derived from the Ramsey study and show the percent of time that drizzle intensity is correctly reported by visibility 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 this event, while 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 again occurred only for the 737-300 engines, and the damage was only to the tips of the fan blades, very similar to the United engine damage. Freezing drizzle is a common occurrence at the new Gardomoen airport due to its location in a valley to the north of the city of Oslo. Thus, engine deicing due to drizzle ingest is fairly common. As a result Braathens has developed a special heated air blower for the 737 engines to remove ice at the gate during these types of conditions. During the event of Feb. 7, 2003, the engines were deiced at the gate with this blower system, but again experienced ice build up 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 – 50 minutes, very similar to the United times. Braathens pilots ran up their engines to 70% N1 at the head of the takeoff runway. All the damaged aircraft experienced engine vibration at this time. The crew continued the engine run-up until the vibration was reduced to acceptable levels and the aircraft took off. The fan blade damage was noticed at the destination airport just as in the United case. Six Braathens 737 aircraft engines were damaged in this fashion during this event. 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. The ice so liberated is centrifuged to the outer portions of the engine where they 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 engines damages (737-300s), and time of taxi. Both cases also had mis-reported weather in terms of either precipitation type or drizzle intensity. Both of these mis-reports led to non-action by the aircraft crew regarding the implementation of engine shedding procedures that are recommended by Boeing Aircraft, United and Braathens airlines under these conditions.

5. ENGINE DAMAGE DURING A WARMER FREEZING DRIZZLE CASE ONE YEAR LATER

On Oct. 31, 2003, another freezing drizzle event occurred at Denver International Airport nearly one year from the date of the first event described above. Six 737-300 engines were damaged during this event, with similar damage. The METAR reported light freezing drizzle during the engine damage period, while the actual rate was again heavy freezing drizzle based on the freezing rain sensor data. The temperature during this event, however, was -3 C, significantly warmer than the Oct. 31 2002 event and the Gardemoen Airport events, which occurred near -8 C. Thus, engine damage is not limited to the cold freezing drizzle events.

6. PROPOSED SOLUTION

The main solution to this problem is the accurate and timely reporting of the correct precipitation type and intensity based on liquid equivalent rate. A real-time version of the Ramsay algorithm described above has been implemented on the Weather Support to Deicing Decision Making (WSDDM) real-time winter weather nowcasting system (Rasmussen et al. 2001). This system provides real-time weather updates at airport locations experiencing winter weather conditions, including a one hour snowfall rate forecast. A new graphic has been added to the system (figure 8) which gives a graphical depiction of the current precipitation type and rate from the Ramsay algorithm. This graphic is updated every minute, and thus provide an accurate estimate of the actual precipitation type (rain, freezing rain, snow, freezing drizzle) and precipitation intensity based on a mass rate of accumulation instead of visibility.

7. CONCLUSIONS

The main conclusions from this study are:

1*) A serious ground deicing hazard has been identified involving the accretion of freezing drizzle on jet engine fan blades and spinners and subsequent shedding during takeoff leading to bent fan blades and other possible damage.* The hazard consists of mis-reporting heavy freezing drizzle as either light snow or light freezing drizzle. If the conditions are properly diagnosed as heavy freezing drizzle, this hazard may be avoided if frequent engine run-ups are performed. The freezing drizzle intensity during the three cases of engine damage presented in this paper was estimated to be heavy. This hazard occurred at a variety of temperatures (-3 to -8 C), indicating that it is not only a cold temperature phenomenon.

2) *The current method to report freezing drizzle on METARS using visibility results in an under-reporting of the freezing drizzle intensity 50% of the time.* Engine run-ups are typically only required if the freezing drizzle intensity is reported as heavy. Thus, future weather system should rely on drizzle intensities determined by a mass basis, such as the Ramsay algorithm applied to the one minute freezing rain sensor data. The Ramsay algorithm has been implemented into the WSDDM winter weather nowcasting system which provides warning of heavy freezing drizzle conditions drizzle every minute based on the ASOS freezing rain sensor.

3) *Freezing drizzle can occur during very light snow conditions, and often reported as light snow due to the difficulty of observing drizzle at the same time as light snow.* Light snow is easily observable by the naked eye, while drizzle is not.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

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Table 1 Denver METARS for the Oct. 31 – Nov. 1, 2002 event

Denver METARs

Date	UTC	Wind direction	Wind speed (knots)	Surface Vsby (sm)	WX	Sky cond	T (C)	Td (C)
10/31	2253	020	09	½	-FZFG	OVC 001	-8	-9
10/31	2353	010	07	1 ¼	BR	BKN 001 OVC 003	-8	-9
11/01	0015	030	06	1 ¼	BR	SCT 001 OVC 003	-8	-9
11/01	0017	030	05	1 ¼	-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 ½	-SN* BR	SCT 002 OVC 004	-8	-9
11/01	0253	050	07	1 ½	-SN* BR	FEW 002 OVC 004	-8	-9
11/01	0353	050	07	1 ¾	-SN BR	OVC 004	-8	-9

Ramsay Algorithm for FZRA/FZDZ

Ice Detector	LEDWI Present Wx Type	Temp	Visibility	Sky Cover	Present Weather Reported
Accretion Frequency < 39,967 Hz and 15 min Accretion Rate >13 Hz in 15 min	RA,UP	<2.8 C (<37°F)	Any	Any	FZRA
	SN	Any	Any	Any	SN
Accretion Frequency < 39,967 Hz and 15 min Accretion Rate >6 Hz in 15 min	No Precip	≤ 0 C (<32°F)	Any	OVC	FZDZ
				Not OVC	None
Accretion Frequency < 39,967 Hz	No Precip	≤ 0 C (<32°F)	≥ 7 miles	CLR or SCT	FROST

Icing Rates

- Generally based on rate per 15 minutes
- .01 inch/hour = 66 Hz/hour = 16.5 Hz/15 min

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

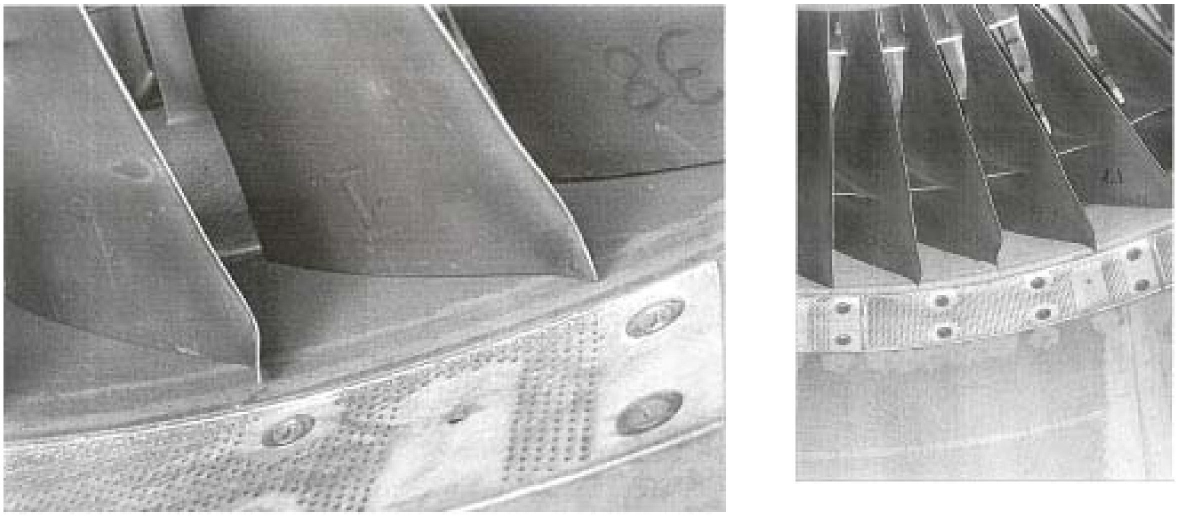

Figure 1 Jet engine damage due to freezing drizzle.

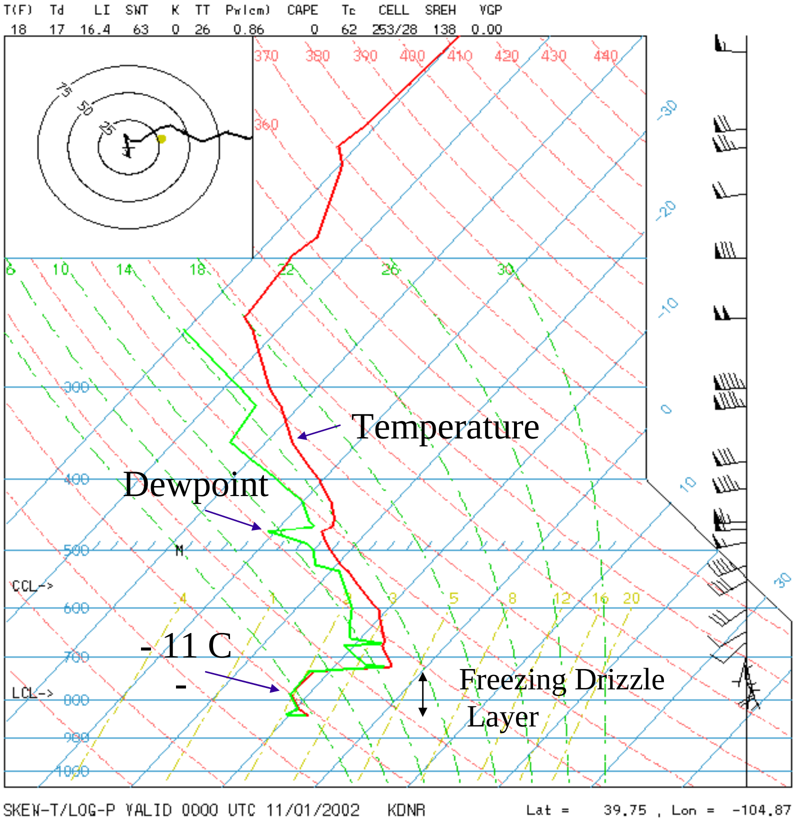

Figure 2 Denver sounding from 00 UTC Nov. 1, 2002

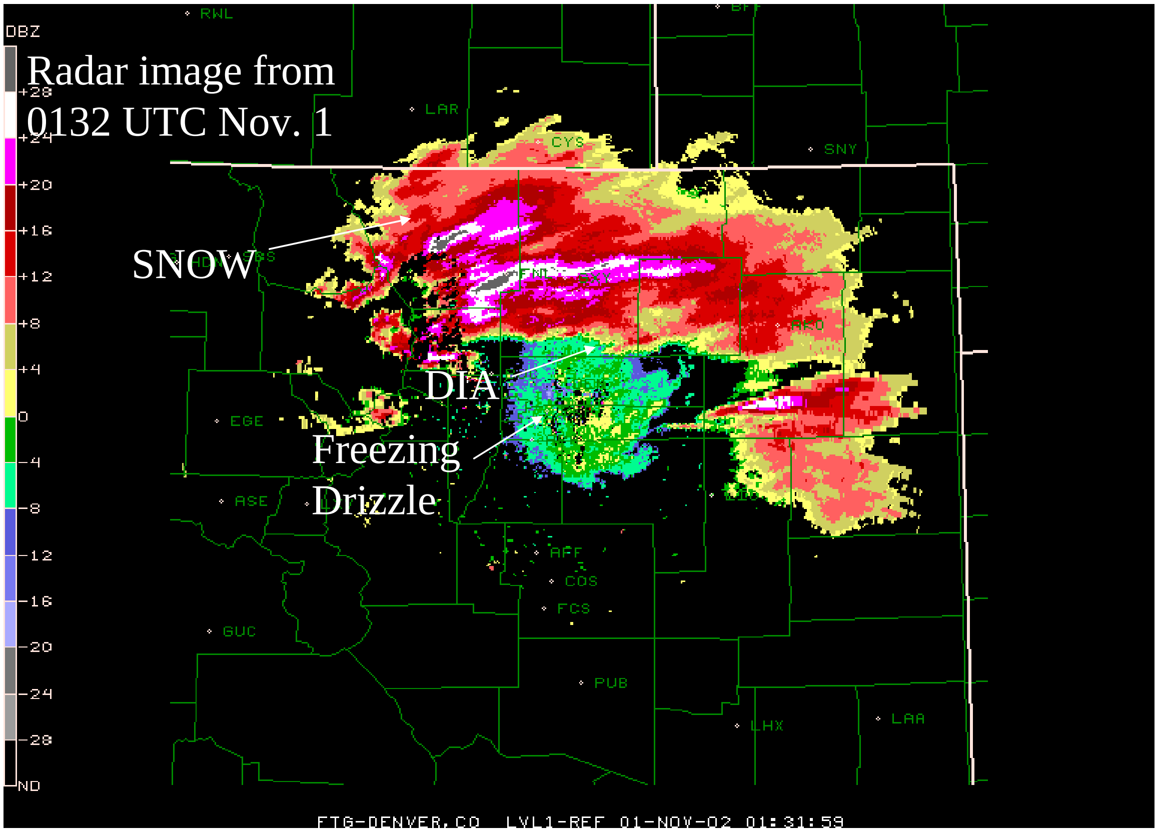

Figure 3 NexRad radar reflectivity from the 0.5 degree scan from 0130 UTC on Nov. 1, 2002

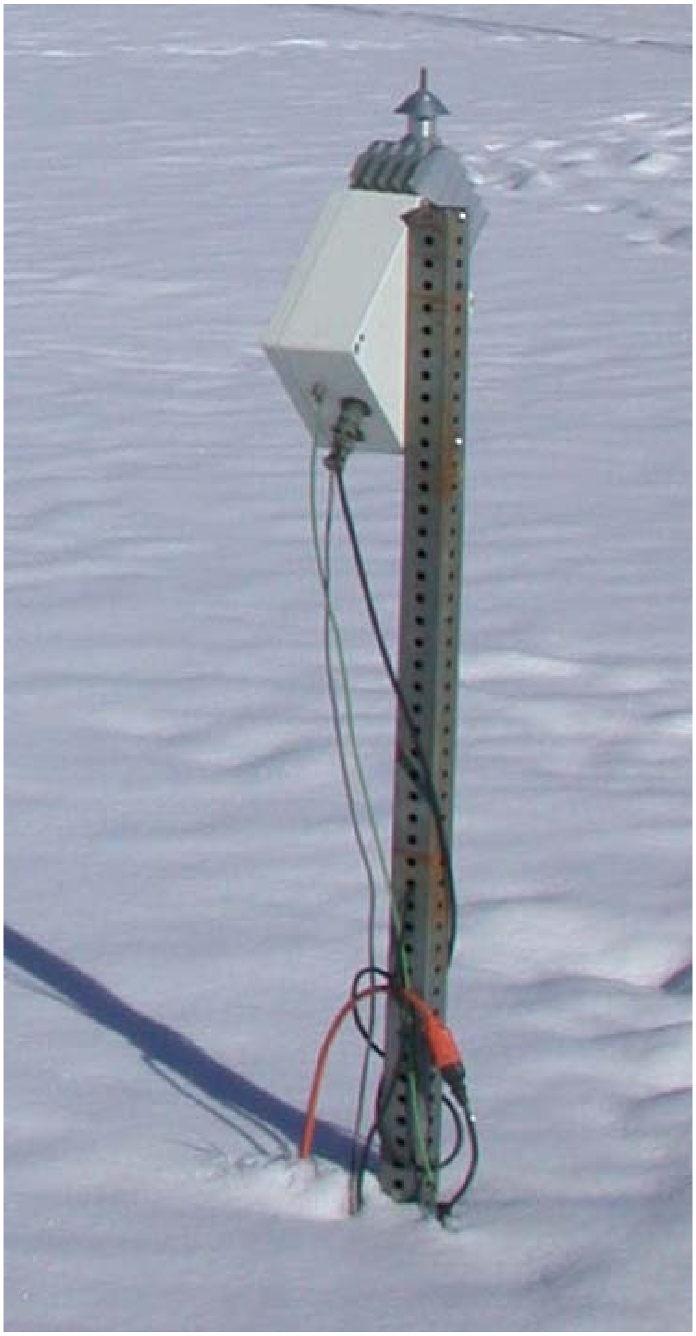

Figure 4   ASOS Freezing rain sensor

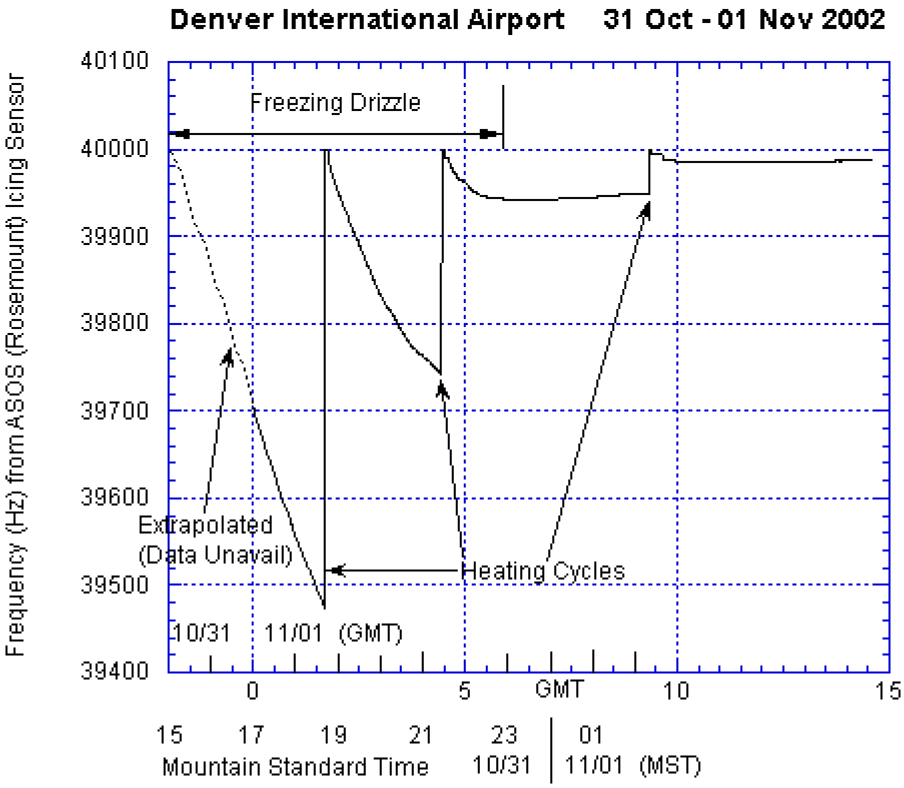

Figure 5 Time series of freezing rain sensor frequency from Oct. 31, 2200 UTC to Nov. 1, 1500 UTC.

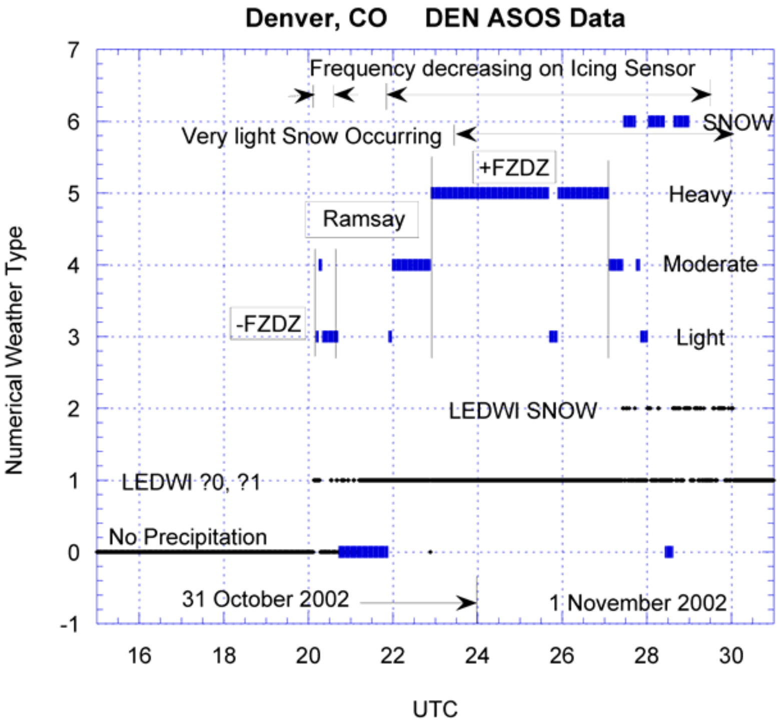

Figure 6. Time series of drizzle intensity from the freezing rain sensor, the LEDWI, and the manual observer from Oct. 31, 2002 1500 UTC to Nov. 1, 2002 0700 UTC.

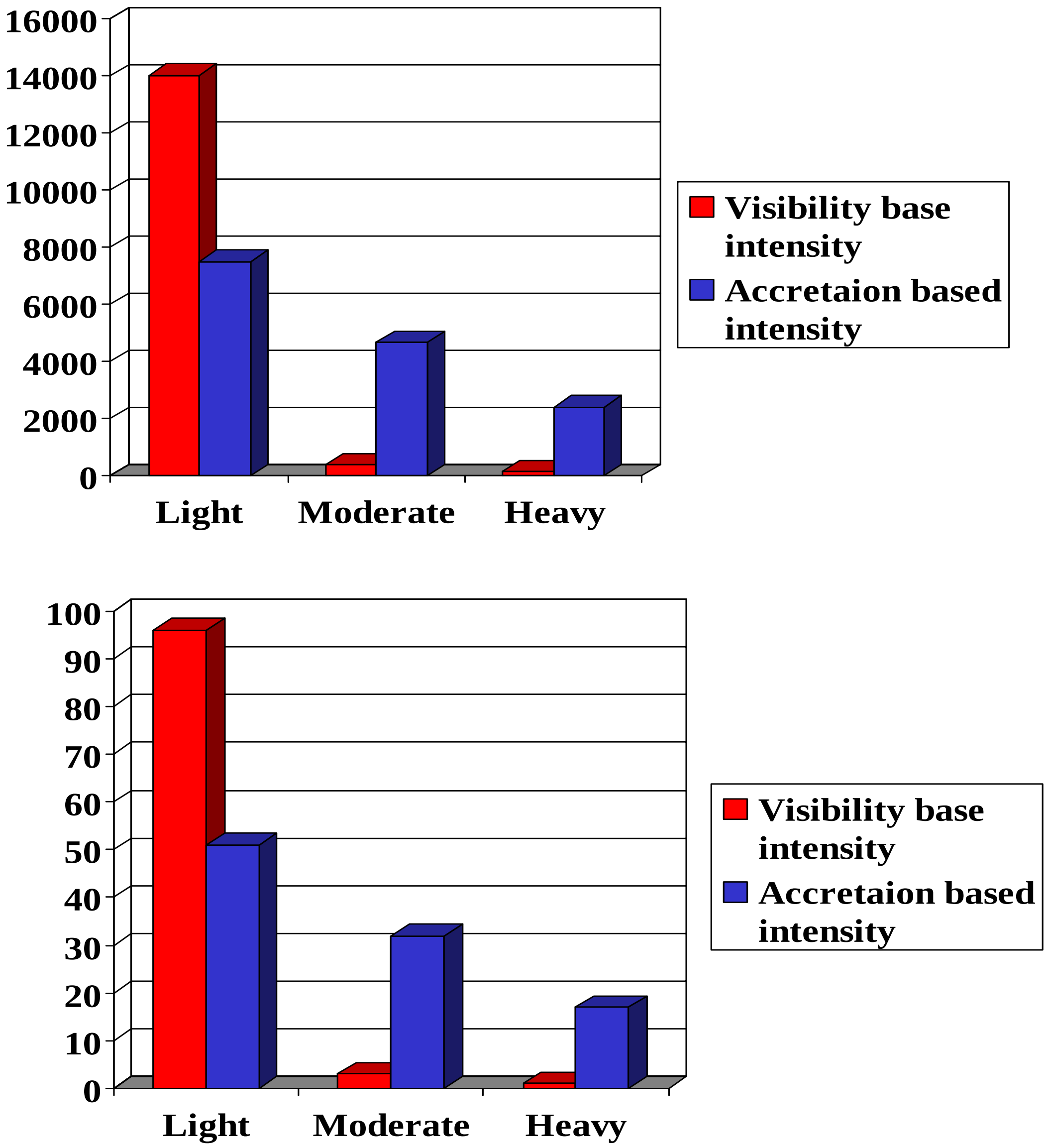

Figure 7 Frequency of freezing drizzle intensity from Ramsay 1999

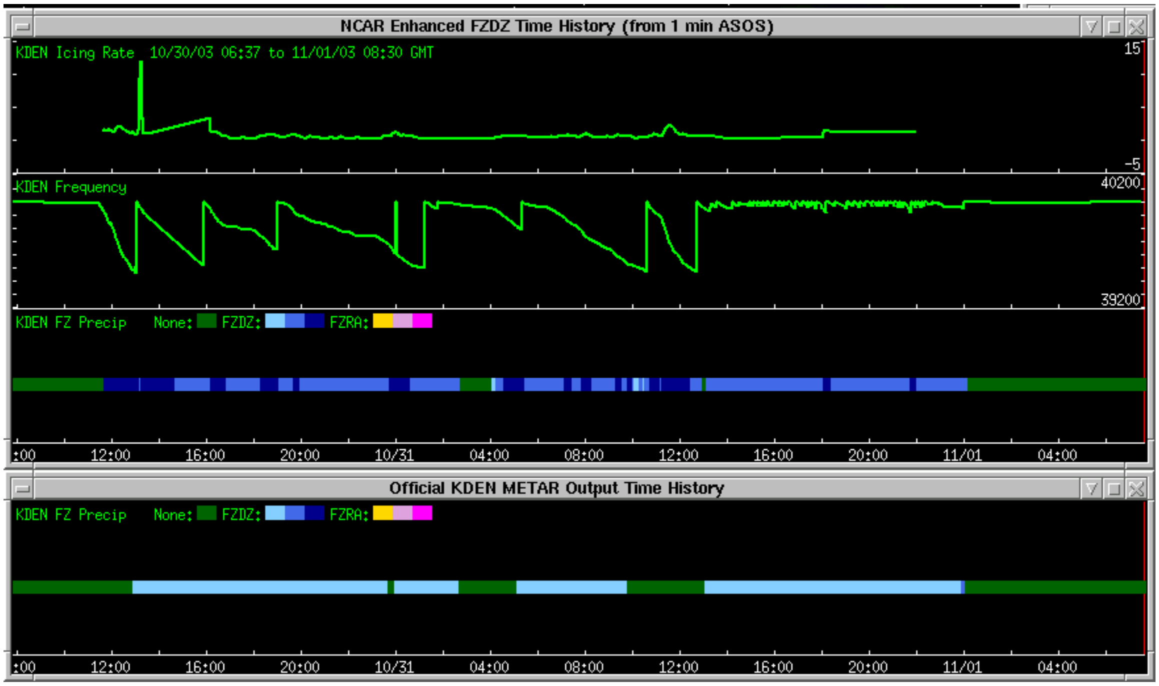

Figure 8 New color coded freezing drizzle, freezing rain diagnostic on the WSDM winter weather nowcasting system.