Evaluation of NCAR Icing/SLD Forecasts, Tools and Techniques Used During the 1998 NASA SLD Flight Season

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August 2001

Available from

Foreword

Supercooled Large Droplet (SLD) icing conditions were implicated in at least one recent aircraft crash, and have been associated with other aircraft incidents. Inflight encounters with SLD can result in ice accreting on unprotected areas of the wing where it can not be removed. Because this ice can adversely affect flight characteristics of some aircraft, there has been concern about flight safety in these conditions.

The FAA held a conference on in-flight icing in 1996 where the state of knowledge concerning SLD was explored. One outcome of these meetings was an identified need to acquire SLD flight research data, particularly in the Great Lakes Region. The flight research data was needed by the FAA to develop a better understanding of the meteorological characteristics associated with SLD and facilitate an assessment of existing aircraft icing certification regulations with respect to SLD.

In response to this need, NASA, the Federal Aviation Administration (FAA), and the National Center for Atmospheric Research (NCAR) conducted a cooperative icing flight research program to acquire SLD flight research data. The NASA Glenn Research Center's Twin Otter icing research aircraft was flown throughout the Great Lakes region during the winters of 1996-97 and 1997-98 to acquire SLD icing and meteorological data.

The NASA Twin Otter was instrumented to measure cloud microphysical properties (particle size, LWC, temperature, etc), capture images of wing and tail ice accretion, and then record the resultant effect on aircraft performance due to the ice accretion. A satellite telephone link enabled the researchers onboard the Twin Otter to communicate with NCAR meteorologists, who provided real-time guidance into SLD icing conditions. NCAR meteorologists also provided pre-flight SLD weather forecasts that were used to plan the research flights, and served as on-board researchers.

This document contains an evaluation of the tools and techniques NCAR forecasters used to predict the location of SLD icing conditions during the winter of 1997-1998. The objectives of this report are to: (1) assess the tools used to forecast in-flight icing, (2) assess the success / failure rate of the forecasts, and (3) discuss suggested changes to forecast techniques.

This report was prepared by Ben C. Bernstein of NCAR.

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Executive summary

This document contains an evaluation of the tools and techniques used by NCAR forecasters to determine the locations of icing and supercooled large drops (SLD) for the NASA-Glenn Twin Otter during the 1998 field season. Twin Otter observations of icing, SLD, crystals, and clear air were objectively and/or subjectively compared to synoptic-scale weather features, surface observations, satellite infrared temperatures and icing algorithm output, pilot reports, the NCAR Integrated Icing Diagnostic Algorithm (IIDA), and more. Also, the ability of NCAR forecasters to direct the Twin Otter into icing and SLD conditions was assessed. Primary results are as follows:

- In 1998, NCAR forecasters guided the Twin Otter into at least some SLD on 61% (28) of the 46 flights, and for 22% of their total flight time. Icing was encountered on every flight day.

- Forecasts for the 1998 field season showed marked improvement over those made for 1997.

- In-flight feedback from NASA was critical to successfully finding and sampling SLD.

- IIDA indicated some icing and SLD potential for 99% and 71% of Twin Otter icing and SLD encounters, respectively. IIDA also did a very good job at differentiating between "yes" and "no" icing and SLD situations.

- IIDA's performance was best below 5000 ft, and decreased somewhat with increasing altitude.

- The NCAR satellite icing algorithm identified 73% of all icing occurrences, while most of the misses occurred in situations where a warm nose and low CTTs were present.

- In the absence of and above a "classical" warm nose, icing and SLD mostly occurred in areas with cloud top temperatures (CTTs) between –16C and –8C.

- Ice crystals and mixed-phase conditions were typically observed with CTTs of –16C to –11C.

- SLD and icing associated with CTTs < -28C nearly always occurred beneath a warm nose.

- Surface observations of freezing drizzle (FZDZ) were an excellent indicator of FZDZ aloft.

- Surface observations of freezing rain (FZRA), ice pellets (PE), and/or rain (RN) were very strong indicators of the existence of FZRA beneath a warm nose aloft.

- The value of surface observations for determining microphysical characteristics aloft decreased with increasing height.

- 87% of FZDZ aloft was observed in the absence of a warm nose, while all FZRA aloft was observed beneath a warm nose.

- FZDZ and FZRA were commonly found ahead of warm fronts and north of stationary fronts. FZDZ found behind cold fronts was typically associated with lake-effect conditions.

- FZDZ and FZRA were nearly always associated with warm advection aloft. Unless lake effect conditions were present, FZDZ did not usually occur with cold advection aloft.

- Radar mosaics typically showed pocketed or no echo > 18dBZ when FZDZ was present aloft.

- Lapse rates were usually between −1.5 and −1.0 C/kft in non-classical FZDZ layers aloft.

- Pilot reports of moderate or greater severity mixed and clear icing were commonly present when SLD was observed aloft, but these PIREPs could not stand alone as an indicator of SLD.

1. Introduction

The purpose of this document is to provide (1) an assessment of the tools used by NCAR meteorologists to forecast in-flight icing and SLD during the 1998 NASA field program, (2) an evaluation of the success/failure of the forecasts, themselves, and (3) suggested changes to forecast techniques for upcoming NASA icing research programs.

2. Assessment of datasets and algorithms commonly used by NCAR forecasters

A brief description of the datasets and algorithms used by forecasters, as well as valuable aspects and shortcomings of them, was provided in the 1997 NCAR forecast evaluation document. Tables and figures throughout the current (1998) document are used to summarize the occurrence of certain weather phenomena that the forecasters typically used, the forecasts provided to NASA, and the aircraft observations made for all 19 icing research flight days. A case-by-case summary is at the end of this document (Table 9). Results in several sections are derived from it. Weather phenomena are compared to the aircraft data in two ways. First, the NASA 2-D Grey probe data were examined in "playback mode" and periods of FZDZ and FZRA were noted. For this portion of the analysis, "deep FZDZ" is noted when in-focus FZDZ was observed though an altitude range of at least 2km, "shallow FZDZ" is noted when in-focus FZDZ covered an altitude range of less than 2km, and "FZRA" is noted when FZRA was encountered aloft. The aircraft observations were then subjectively compared to the weather phenomena that occurred in the vicinity of the aircraft.

A second, more objective analysis was done on a minute-by-minute basis. Tammy Langhals of NASA-Glenn visually inspected 2D-Grey "dump" plots to determine the presence of drizzle, rain, and ice crystals, and time series plots of the Rosemount ice detector voltages for the occurrence of cycling (icing). The results were merged with uncorrected 1-minute averages of static temperature, King LWC (zero removed), FSSP and 2D-Grey concentrations, and altitude. The matched information was then broken down into three categories based upon the vertical temperature structure of the atmosphere within the four Rapid Update Cycle (RUC) model grid points that surrounded the aircraft at that time.

Category 1 – A classical freezing rain ("warm nose") structure was *not* present at all four of the RUC points. This is considered to be a "non-classical" situation, where the collision-coalescence process should be responsible for the formation of any SLD observed by the aircraft and at the surface (FZDZ, FZRA). If the classical freezing rain structure was present at any of the four RUC points, then a melting scenario is possible.

Category 2 – A warm nose was present at any of the four points, and the aircraft was at altitudes *below the highest warm nose*. At these altitudes, any SLD observed was likely to have been formed by the classical melting process. The exception would be if SLD was formed above the warm nose, then fell into the altitudes beneath it.

Category 3 – A warm nose was present at one of the four points, and the aircraft was at altitudes *above the highest warm nose*. At these altitudes, the aircraft was above the melting zone, so non-classical processes were likely to have produced any SLD observed there.

For each minute of flight data, the occurrence of icing and SLD was determined, and a confidence level identified, ranging from 0 to 3. ICE-1 was assigned if the temperature was subfreezing for the entire minute, and any of the six 10-second average LWC values was at least 0.025 (raw King probe data with "zero removed"). ICE-2 was assigned if the criteria for ICE-1 were not met, yet visual inspection of the ice detector trace showed that it was cycling during that minute. ICE-3 was assigned if the criteria for ICE-1 and -2 were both met, indicating the highest confidence that icing occurred. ICE-0 was assigned if the criteria for neither ICE-1 nor -2 were met, indicating a high confidence that icing did not occur. SLD confidence was determined using a combination of information from the visual inspections of 2d-grey imagery and values from the temperature and FSSP probes. The possibility that FZDZ or FZRA were present was initially based upon whether or not drizzle- or rain-sized circles were observed in combination with entirely subfreezing temperatures during a given minute. If these criteria were met and no ice crystals were present, then the highest confidence level (SLD-3) was assigned, since the circular images were very likely to have actually been SLD. If crystals were present, but the FSSP showed that cloud-sized particles were not, yet the LWC was at least 0.05 g m^{-3}, then the large circular images were likely to be the source of the LWC measured, and thus were fairly likely to be SLD. However, the presence of ice crystals and possible ambiguities in LWC measurements casts some doubt, so SLD-2 was assigned. If the FSSP indicated that cloud particles were also present, then the confidence is even lower that any large particles were liquid, so SLD-1 was assigned. If no drizzle- or rain-sized droplets were present, then SLD-0 was assigned. For this document, only results for ICE-3, ICE-0, SLD-3, and SLD-0 are discussed, since those categories have the least ambiguity regarding the existence/lack of icing and SLD.

A - SURFACE OBSERVATIONS - *Subjective analysis*

Freezing drizzle (FZDZ) – During the 1998 season, FZDZ was observed in the vicinity of the aircraft on 6 of the 19 days (see Table 1). The aircraft observed deep layers of FZDZ on all 6 of those flights, confirming surface observations of FZDZ as a very strong indicator of FZDZ aloft. During 1997, two flights were made in the vicinity of surface observations of FZDZ. In the one case where "Cloud" (no SLD) was indicated, the surface FZDZ was to the northeast, while the aircraft passed through an area of snow in an attempt to reach it (970314). By the time the aircraft reached the area where the FZDZ was observed, snow had taken over.

Drizzle (DZ) – Drizzle was observed at the surface in the vicinity of the aircraft during 7 cases during the 1998 season, and 9 cases overall. Deep FZDZ was observed in 4 of those cases, while another 2 had shallow FZDZ. In all six of these cases, warm cloud top temperatures (CTT) greater than -15C were present, indicating that collision-coalescence was the probable formation mechanism of the FZDZ aloft, and subsequent DZ at the surface. With colder cloud tops, the formation mechanisms for the surface DZ and the potential for FZDZ aloft was less certain. Melting of small snowflakes may have been the cause of the

surface DZ in the remaining cases where FZDZ was not observed aloft. FZRA observed aloft on DZ cases occurred in different time periods and/or locations from the surface DZ.

Freezing Rain (FZRA) - FZRA was observed at the surface in the vicinity of flights during 4 cases in 1998, and 8 cases overall. FZRA was encountered aloft in 5 of those cases where the layer under the melting zone was sampled. In one case where it was not encountered, the aircraft did not sample the area below the melting zone where the surface FZRA was reported (north of the flights). Altitudes above the warm nose were sampled on 980205 because the FZRA layer appeared to be too shallow and/or warm for adequate aircraft sampling. Some FZDZ was found both above and below the potential melting layer near Zanesville when a hole in the radar echo developed. In the two cases where FZRA was reported at the surface and no SLD was found aloft, the altitudes below the warm nose were not sampled in the vicinity of the surface observation of FZRA (2/4/97 and 3/13/97 cases).

Ice Pellets (PL) –PL was observed at the surface during 3 cases in 1998, and 5 cases overall. In 3 cases, FZRA was observed beneath the melting zone. In the case where no SLD was observed aloft, the PL was observed in the vicinity of the aircraft, but not beneath it. Shallow ZL was observed aloft in one instance, but did not appear to be associated with the PL.

SURFACE PRECIPITATION TYPE

	1998	FZDZ	FZRA	PE	DZ	RA	SN	OVC	TOT
Conditions aloft	Deep FZDZ	6	2	0	2	4	5	10	10
	Shallow FZDZ	0	1	1	2	2	3	3	3
	FZRA	0	3	2	1	2	2	3	3
	No SLD found	0	0	0	2	3	3	4	4
	TOTAL	6	4	3	7	11	13	19	19

	1997+1998	FZDZ	FZRA	PE	DZ	RA	SN	OVC	TOT
Conditions aloft	Deep FZDZ	6	2	0	4	6	6	13	13
	Shallow FZDZ	1	1	1	2	2	4	5	5
	FZRA	0	5	3	2	3	4	5	5
	No SLD found	1	2	1	2	5	8	11	11
	TOTAL	8	8	5	9	15	21	32	32

Table 1 – Number of flights where surface precipitation types were observed to be coincident with aircraft-observed microphysical conditions aloft.

Rain (RA) and snow (SN) – Non-precipitating or lightly precipitating cloud along the edges of areas of RA and/or SN proved to be quite favorable for icing and SLD. In 1998, SLD was observed aloft in 8 of the 11 RA cases, and 10 of the 13 SN cases, nearly always along the edges of the precipitation, where holes in the echo or transitions to non-precipitation cloud. The exception cases were those where RA

and/or SN was observed at the surface in or near classical FZRA situations. In those cases, the SLD was observed within the areas of precipitation. Overall, a wide variety of conditions were observed aloft of and in the vicinity of surface observations of RA and SN. The forecaster often could not be sure of what would be present aloft, except when a classical FZRA structure was present.

Cloud cover - OVC conditions were observed in flight locations during all 19 of the 1998 cases, and all 32 cases for the two seasons combined. Icing was observed during all of those events, while at least some SLD was observed during 15 of them in 1998, and 23 of them for both years combined.

B - SURFACE OBSERVATIONS - *Objective analysis*

Minute-by-minute objective matching of Twin Otter encounters and surface observations was done using the position of the aircraft to determine which surface stations were within 100, 50, and 25km of it. The precipitation types and cloud cover reported by the stations at the top of the hour were then matched to the aircraft observations. Thus, aircraft data from 1600-1629 UTC were matched to the 1600 UTC surface data, while the 1630-1659 UTC aircraft data were matched to the 1700 UTC surface data, etc. It is important to note that this approach causes a certain amount of redundancy in the data. If the plane loitered over a certain location, then the same surface observation may be matched to aircraft data for 60 data points. In general, this was not the case. At a typical cruising speed of 120 knots, the aircraft traversed 216 km per hour of straight-line flight. Using a 50-km radius and assuming that the aircraft flew directly over the station at the top of the hour, the same surface observation would have been matched to 28 minutes of aircraft data. These examples demonstrate the high-end amounts of redundancy expected in the data.

Surface observations were not available for certain hours, and the aircraft data matched to those times are not included here. Overall, 3939 minutes (65+ hours) of aircraft data are included in this analysis, and the aircraft was within clouds and/or precipitation at subfreezing temperatures during 3631 (92%) of those minutes. Only that subset of times is used here. Precipitation types were subcategorized as follows: FZDZ, FZRA, ice pellets (PE), any freezing precipitation (ALZ = FZDZ, FZRA, or PE), snow (SN), rain (RN), rain or snow (ROS), snow only (SNO – no other precipitation types reported), classical precipitation (ZIR = FZRA, PE, or RN), drizzle (DZ), any precipitation type (ANY), and overcast skies (OVC). The aircraft data were subdivided by altitude ranges (0-5000 ft, 5000-10000 ft, 10000+ ft, all altitudes). The matrices that resulted from this analysis are large, to say the least.

For the purposes of brevity, table 2 only shows results for meteorological categories 1 and 2 (described earlier), all aircraft altitudes, using a 50km radius for surface observations. Only a few highlights will be discussed here. Categories 1 and 2 were chosen because 100% of the FZRA and 91% of the FZDZ observed aloft occurred when these criteria were met. Overall, 87% of all FZDZ observed aloft (330 minutes) occurred in the absence of a warm nose (CAT-1), and all of FZRA observed aloft (249 minutes) occurred when the RUC indicated that a warm nose was present and the aircraft was beneath this feature (CAT-2). In table 2, the FZRA/FZDZ category is for those times when both rain- and drizzle-sized drops were observed (typically a FZRA situation where FZDZ droplets were a part of the FZRA drop size spectrum), while the "FZDZ only" and "FZRA only" categories are for those times when only one drop size

range was observed. When no surface observations were found within the radius (50km in this case), that minute is placed into the "NOB" category.

The strength of certain surface indicators as predictors of conditions aloft can be inferred by dividing the number of times that the conditions were observed aloft during those surface conditions by the total number of times those conditions occurred within the radius considered. For example, of the 307 minutes that RN occurred within the 50km radius (CAT-1), ICE-3 was present 61 of those times, or 20% of the time. An idea of how much a surface condition accounts for the occurrence of a condition aloft can be gained by dividing the number of times they were coincident by the number of times the condition aloft was observed. For example, of the 697 times that ICE-3 was present and a surface station was within 50 km (771 TOT – 74 NOOBS), overcast sky cover (OVC) was reported 667 times, or 96% of the time.

CAT-1: To continue the results for OVC described above, ICE-3 was present aloft 31% of the time that OVC was reported within 50km. Thus, while OVC conditions are almost always present when icing is definitely present aloft, the occurrence of an OVC observation does not guarantee that icing will be found. In fact, icing was definitely not present (ICE-0) 45% of the time when OVC conditions were present. Of the times when icing definitely was present (ICE-3), precipitation of any type (ANY) was present 78, 47, and 28% of the time within 100, 50, and 25km, respectively. This trend shows that most icing occurred in the vicinity of precipitation (within 100km), but that it tended to occur around the edges of the precipitation, rather than right in it. NCAR forecasters have observed this on a routine basis during flight operations. This trend was especially strong for the SNO and ROS categories, but little or no trend was present for the ALZ (any freezing precipitation) category. Thus, icing was just as likely to be present aloft when freezing precipitation occurred within 100km, as it was when it occurred within 25km.

When FZDZ was the only type of SLD observed aloft ("FZDZ only"), some surface precipitation (ANY) was found within 100km about 85% of the time, but this number decreased with decreasing radius, similar to the results seen for ICE-3. This trend is reversed for surface observations of FZDZ, going from 29% at a radius of 100km to 45% and 46% at radii of 50km and 25km, respectively. The connection between FZDZ aloft and at the surface is strongest at altitudes of 5000 feet or less, with values of 38%, 63%, and 70% at 100km, 50km, and 25km radii. This shows that such observations become stronger indicators of FZDZ aloft as the aircraft flies closer to them, and that they were in FZDZ aloft 63% (70%) of all the minutes that the aircraft flew within 50 km (25 km) of a surface observation of FZDZ. On the flip side, only 12% of all FZDZ encountered aloft was coincident with surface FZDZ. It is important to note that nearly all of the minutes when FZDZ was observed simultaneously aloft and at the surface occurred during one event (971211). ASOS problems with detecting and reporting FZDZ caused trouble with the statistics, since FZDZ was misreported as FZRA at Green Bay WI on 980126, and at Canton-Akron OH on 980130. Both were clearly cases of collision-coalescence, and the aircraft observed drop sizes in the drizzle range all the way to the surface. These additional observations account for all of the occurrences of FZDZ aloft with "FZRA" at the surface in CAT-1. Thus, since PE were never reported in CAT-1, the 18% (54 out of 299 minutes) reported for ALZ represents the amount of time that FZDZ aloft was associated with FZDZ at the surface. FZDZ aloft was often associated with overcast sky conditions without any precipitation reported

within the 50km radius (OVC-ANY = 135 out of 299 minutes, 45% of the time). In general, these results show that while surface observations of FZDZ are a very strong indicator that FZDZ will be found aloft, especially in the lowest 5000 feet, the majority of the FZDZ observed aloft was not explained by surface observations of FZDZ.

Finally, encounters with ice crystals aloft were fairly well tied to the occurrence of SNO at the surface. Of the times that SNO observations were taken at the surface, ice crystals (XLS-4) were present 40%, 45%, and 58% of the time for radii of 100km, 50km, and 25km, respectively. Ice crystals were present in the lowest 5000 feet 66% of the time that SNO was observed at the surface within 25km. Also, of the times that ice crystals were observed aloft, ROS was present within 100 km at the surface 83% of the time. This number decreased to 54% and 42% at radii of 50km and 25km, indicating that the rain or snow (ROS) was typically observed in the vicinity (100 km), but not necessarily immediately beneath the aircraft when ice crystals were observed aloft. Also, as the aircraft flew closer to surface observations of ROS, the percentage of time that ice crystals were observed aloft increased from 43% to 58%, while the number of minutes without ice crystals reversed accordingly (from 57% down to 42%).

CAT-2: Meteorologically, the presence of a warm nose structure is a strong indicator of the classical melting process, and that FZRA is likely to be found beneath it when FZRA, PE, and/or RN (ZIR) occur at the surface. The results shown here bear this out. When FZRA was encountered aloft, ZIR was observed at the surface 100%, 80%, and 70% of the time when surface observations were found within 100 km, 50 km, and 25 km, respectively. While the downward trend with decreasing radius is somewhat puzzling, these statistics still show that most of the FZRA aloft is explained by the combination of the warm nose structure with the occurrence of these surface precipitation types. Of all times when ZIR occurred at the surface, FZRA was encountered aloft 46%, 57%, and 59% of the time. Stronger results were found when considering only PE (62%, 95%, and 93%) or RN surface observations (59%, 66%, 72%), while weaker results occurred for surface observations of FZRA (36%, 29%, 30%). In most cases, the FZRA aloft did not extend down to the surface, often reaching it as rain due to above freezing temperatures near the surface. Ice crystals were typically not found beneath the warm nose, but when they did show up, they were primarily associated with surface observations of snow. Such observations are often found on the cold side of sharp transition zones which occur with classical freezing precipitation.

CONDITIONS OBSERVED ALOFT

	CAT-1 50km	ICE-0	ICE-3	SLD-0	FZDZ only	FZRA only	FZRA & FZDZ	XLS-0	XLS-4	Total
SURFACE PRECIPITATION TYPES	FZDZ	4	20	20	35	0	0	47	30	77
	FZRA	11	56	42	19	0	0	60	21	81
	PE	0	0	0	0	0	0	0	0	0
	RN	160	61	120	22	0	0	119	188	307
	SN	187	228	239	127	0	0	340	264	604
	DZ	6	2	8	1	0	0	8	2	10
	OVC	947	667	1129	294	0	0	1317	802	2119
	ALZ	15	76	62	54	0	0	107	51	158
	ROS	338	289	359	149	0	0	459	440	899
	SNO	184	217	228	100	0	0	305	246	551
	ZIR	171	117	162	41	0	0	179	209	388
	ANY	347	326	388	159	0	0	497	456	953
	TOT	1115	771	1391	330	0	0	1607	867	2474
	NOB	76	74	138	31	0	0	162	52	214

	CAT-2 50km	ICE-0	ICE-3	SLD-0	FZDZ only	FZRA only	FZRA & FZDZ	XLS-0	XLS-4	Total
SURFACE PRECIPITATION TYPES	FZDZ	0	0	0	0	0	0	0	0	0
	FZRA	62	15	47	11	0	25	81	5	86
	PE	0	57	2	1	0	57	60	0	60
	RN	24	168	68	5	4	162	236	14	250
	SN	90	35	70	8	0	43	88	80	168
	DZ	2	0	2	0	0	1	3	0	3
	OVC	197	224	215	25	6	228	437	114	551
	ALZ	62	72	49	12	0	82	141	5	146
	ROS	104	180	125	13	4	180	287	88	375
	SNO	82	17	58	8	0	23	56	78	134
	ZIR	86	183	115	16	4	187	317	19	336
	ANY	150	195	165	22	4	196	350	93	443
	TOT	206	230	224	25	6	243	460	115	575
	NOB	7	3	7	0	0	9	16	0	16

Table 2 – Number of minutes where surface precipitation types was observed to be coincident with aircraft-observed microphysical conditions aloft.

Results for 1998 NASA flights in the vicinity of certain surface map features are given in the first table below, while those for the 1997 and 1998 seasons combined are given in the second. In this analysis, encounters with in-focus FZDZ (whether deep or shallow), FZRA, and non-SLD ("cloud") cases are broken down by location relative to fronts, troughs, and lows. If lake effect conditions appeared to play a role in the area of flight, then the case was also put into the LEF category. Cases of "borderline FZDZ" from the 1997 analysis were put into the "Cloud" category, since no in-focus FZDZ was noted. There were not enough data points from 1998 alone to draw valuable conclusions, but by combining the two flight years, we can gain some insight.

The areas ahead of warm fronts (AWF), and to the north of stationary fronts (NSF) continued to be good spots for both FZDZ and FZRA to occur, while "cloud-only" cases were not observed in these locations in two seasons. These locations tend foster combinations of lifting, cloud top temperatures, and temperature structures that favor FZDZ and/or FZRA. The areas surrounding surface lows (LOW), surface troughs (ST), and especially along (OST) and ahead of (AST) troughs prove to be common sites for FZDZ, and sometimes FZRA, aloft. Some SLD is found behind surface troughs (BST), as well, but the dominance of SLD occurrences rather than only cloud drops is not as evident there.

		SURFACE WEATHER CHART FEATURES											
	1998	**ACF**	**BCF**	**AWF**	**BWF**	**NSF**	**SSF**	**OCC**	**AST**	**OST**	**BST**	**LOW**	**LEF**
ALOFT	FZDZ	2	1	2	1	2	1	1	3	2	3	2	3
ALOFT	FZRA	0	0	0	0	2	0	0	0	0	2	1	0
ALOFT	Cloud	1	0	0	0	0	0	1	0	1	2	0	1

	97+98	**ACF**	**BCF**	**AWF**	**BWF**	**NSF**	**SSF**	**OCC**	**AST**	**OST**	**BST**	**LOW**	**LEF**
ALOFT	FZDZ	2	3	5	2	4	1	1	4	6	3	3	4
ALOFT	FZRA	0	0	2	0	2	0	0	0	1	2	2	0
ALOFT	Cloud	2	4	0	0	0	0	1	0	1	2	1	3

Table 3 – Number of cases where aircraft-observed microphysical observations aloft were matched to synoptic-scale surface weather chart features. A = ahead of, B = behind, N = north of, S = south of, CF = cold front, WF = warm front, SF = stationary front, OCC = occluded front, ST = surface trough, LOW = surface low, LEF = lake effect.

The areas surrounding cold fronts had a fairly even chance of having FZDZ or only cloud drops. In most of the FZDZ observed behind cold fronts (BCF), lake effect conditions (LEF) were also in place. When the LEF was not present, small drops tended to be observed BCFs. LEF conditions may have supplied a cleaner air source with fewer CCN. Combining this with the steep lapse rates and high LWC that were sometimes present BCFs, the high water contents probably had fewer sites to grow upon, and

produced FZDZ more readily. When there are a lot of CCN, the high water contents are distributed among many more droplets, keeping them small. LEF is not a strong enough predictor by itself. In nearly half of all lake effect cases, only cloud drops and/or ice crystals were observed.

D - GOES-8 SATELLITE DATA

Visible – Via static images and loops, visible satellite imagery provided an indication of the location, movement, coverage and character of clouds. As described in the section on surface observations, overcast cloud cover was important and visible imagery was used to identify discontinuous and/or dissipating clouds. The character of the cloud top was also sometimes discernible, including whether the cloud was convective or stratiform in nature, and where changes in the character of the cloud cover existed. The major shortcoming of visible imagery was that it was not typically available before 1300 or 1400 UTC during the field season, simply because the sun was not up. Since briefing time was typically 1200 UTC, this limited the use of visible imagery to forecast updates and in-flight guidance.

Infrared - Infrared (IR) satellite data provided the temperature of cloud top in cloudy situations and the surface (ground, water, snow cover) in non-cloudy situations. Cloud-top temperature (CTT) was extremely useful for making a first-guess at the microphysical composition of a cloud. CTTs > –10 C nearly always indicated the existence of liquid water, while CTTs < –25 C nearly always indicated the existence of ice crystals near cloud top. In the intermediate –25 < CTT < -10 C range, liquid water and/or ice crystals could form near cloud top, with warmer and colder CTTs having a higher likelihood of being associated with liquid water and ice crystals, respectively. The major shortcoming of infrared satellite data was that it only provided the CTT of the highest cloud (closest to the satellite) and no information was available about lower cloud decks when multiple cloud decks exist, or about freezing rain layers if a warm nose existed. This caused lower layers of icing and SLD to be obscured by higher cloud that was unlikely to contain icing (e.g. cirrus or deep, cold, snow clouds).

Results from comparisons between Twin Otter data and GOES-8 IR values bear this out quite well. For each minute the aircraft was in clouds and/or precipitation (observed particles in the FSSP and/or 2D-Grey probe), the satellite-measured IR temperatures were acquired for a 12x12 pixel (48km x 48km) square surrounding the aircraft. An adaptation of the yes/no cloud algorithm described in McDonough and Bernstein (1999) was applied to each pixel. The mean IR temperature for all of the "cloudy" pixels was calculated, and compared to the icing and SLD confidence levels. Finally, the RUC-model vertical temperature structures for the four grid points surrounding the aircraft were checked for the occurrence of a classical freezing rain structure. Each minute was further categorized into those with no warm nose (CAT-1), and those where the aircraft was below (CAT-2) or above (CAT-3) the warm nose when one existed. These categories allow for the determination of whether or not the icing and/or SLD were brought about by classical or non-classical mechanisms.

The distributions of mean IR cloud top temperatures (CTTs) for ICE-3 and SLD-3 show that when icing occurred in the absence of a warm nose (black bars in Fig. 1a,b), CTTs were generally above –24C,

with the most falling into the –16C to –8C range. Similar results were found for the relatively few occurrences of icing/SLD at altitudes above a warm nose (hatched bars), where melting did not play a role in the formation of the supercooled liquid water. The few cases of icing with CTT < -25C, either without or above a warm nose, appeared to occur in situations with multiple cloud decks, where the aircraft flew within lower clouds that were not visible to the satellite due to obscuration by higher clouds (e.g. 980205 icing and FZDZ above the warm nose near Zanesville). When CTTs were below –25C, essentially all of the icing/SLD occurred beneath a warm nose (gray bars).

Of course, since the forecasters were well aware of the fact that certain situations were likely to be associated with icing and SLD, the aircraft was often directed into them. A distribution of the number of flight minutes within clouds and/or precipitation versus mean CTT demonstrates this fact (Fig. 2). This places a bias into the sample which could lead to the appearance of more icing in certain CTT bins simply because the aircraft flew within these conditions more often, not because the conditions are more conducive to icing/SLD. To address this, the icing/SLD minutes were normalized by the total number of minutes flown within clouds and/or precipitation at each mean CTT. Resulting values are the percentage of minutes flown at a given CTT that had icing/SLD (Fig. 3a,b). Icing was observed 30-50% of the time the Twin Otter flew in areas with mean CTTs between –17C and –7C, and all of this icing occurred either without a warm nose, or above one. High percentages were also found for temperatures between –24C and –20C, but this was based on very few samples (see Fig. 2). While a large percentage of the time flown in areas with CTTs < –28C resulted in icing, nearly all of it was found beneath a warm nose. SLD percentages followed somewhat similar patterns, but were typically lower by a factor of three for the warm CTTs, and higher for the very cold CTTs (<-42C).

It is also interesting to examine conditions in which the aircraft encountered ice crystals and mixed-phase conditions (Fig. 4a,b). The overall distribution shows that they were most commonly observed in the –16C to –11C range, which were on the colder end of the ICE-3 CTT distribution. Ice crystals, but very little mixed phase conditions, were found above or without warm noses with CTT < -32C, where very little icing/SLD was found. Some ice crystals were encountered beneath warm noses, and were likely attributable to the sharp transitions in precipitation type often found in these situations, incomplete melting of crystals falling through the warm nose above, and/or nucleation in cold, dirty air near the surface. For the most part, the ice crystals encountered beneath the warm nose were observed in mixed phase conditions. Overall, these results show similar patterns to those found earlier, and these basic conclusions remain:

- When icing or SLD occurred in the absence of a warm nose, or above a warm nose, CTTs were generally –16C or warmer
- Icing was likely to be encountered when the aircraft flew into clouds with CTT > -16C,
- Icing/SLD was nearly always confined to beneath a warm nose structure when cold cloud tops were present, and
- Ice crystals and mixed-phase conditions tended to be encountered with colder CTTs, including those on the colder end of the icing spectrum for CAT-1 and CAT-2.

Icing algorithm – GOES-8 provides information from several frequencies/channels that can be useful in the diagnosis of icing. NCAR and other organizations have created techniques that combine the information from several of these channels to differentiate clouds from other features (snow cover, ground, water), as well as to identify cloud tops which are likely to be liquid (rather than crystalline) in type at subfreezing temperatures. The algorithm has been useful for identifying the horizontal locations of icing at cloud top. Twin Otter samples of the edges of indicated icing clouds have borne out the algorithm's ability to do so. Its shortcomings were the same as those listed for visible imagery, and that it was not available until the sun was well above the horizon. A less robust nighttime version was available, but no information on icing was available within the solar "terminator". One of the parameters used in the development of the algorithm (channel 2 reflectance) has been theoretically shown to have promise for identifying larger droplet sizes at cloud top. This technique has yet to be rigorously tested.

If the solar zenith angle was large enough (cos(a) > 0.259) over a given pixel, then it was considered to be in daylight. If all 144 pixels were in daylight, then the individual pixels were checked to see if the NCAR satellite icing algorithm indicated "icing" or not. The percentages of pixels that had "icing" were then compared to concurrent aircraft observations for the three categories discussed earlier. Overall, when ICE-3 was observed, the satellite algorithm indicated icing for at least 1% and 30% of the 144 pixels 74% and 73% of the time, respectively (Fig. 5). Most of the misses were attributable to icing beneath the warm nose (26% of all ICE-3 minutes), when cloud tops were primarily composed of ice and had relatively low CTTs (<-25C). When considering only the icing observed in the absence of a warm nose (CAT-1) and above the warm nose (CAT-3), the satellite algorithm indicated "icing" in at least 20% of the pixels 97% of the time, at least 50% of the pixels 91% of the time, and for every pixel 52% of the time. The algorithm did an excellent job of depicting at least a chance of icing in these situations. However, it missed essentially all icing that occurred beneath a warm nose during the classical precipitation process, and it provided no indication of icing altitudes or depth. For these analyses, no measure of overwarning was made.

It is important to note that the redundancy of the data should be considered for all of the satellite fields tested, since the aircraft could have been compared to the same satellite pixels as many as 30 times. Assuming level, straight-line flight at a ground speed of 120 knots (60 ms^{-1}), the aircraft traversed more than two entirely different boxes of satellite pixels (108 km, while each box is 48 km wide) during the 30 minutes that each satellite sample was valid. Thus, redundancy may not be a serious issue for these data.

E - NEXRAD RADAR MOSAICS

For each icing event in the dataset, the mosaic radar echo in the vicinity of the aircraft sampling was characterized as "solid" (completely filled echo pattern), "pocketed" (gaps and/or edges in the echo pattern), "banded" (distinct bands were evident in the echo) or "no echo" (no echo was present). Comparisons of the radar echo character with the icing environment encountered by the Twin Otter are given below. Mosaic data were not available for 2/4/97 (a case with in-focus FZDZ aloft - pocketed echo was evident in Cleveland NEXRAD data, so this case was counted in the "pocketed" category), or 2/5/97

(a mostly small-drop icing case with brief pockets of in-focus FZDZ – this case was not counted in any category). In addition, bad probe data for 3/25/97 did not allow for an indication of whether FZDZ or FZRA was present.

Both deep and shallow FZDZ primarily occurred in situations with pocketed echo or no echo (>18dBZ). When pockets were present, the FZDZ was found within holes in the echo, or along its edges. FZDZ was noted with bands (or swaths) of radar echo, and even "solid" echo. In both situations, the FZDZ was typically found along the edges or outside of these echo regions. By themselves, a lack of echo, pocketed, or banded echo were definitely not indicators that FZDZ would occur aloft, as was evident by the nearly identical number of occurrences of only small-drop icing in these scenarios. FZRA almost exclusively occurred in solid echo, but was also observed once within pocketed echo.

	RADAR ECHO FEATURES			
1998	**None**	**Pockets**	**Band(s)**	**Solid**
Deep FZDZ	2	5	1	1
Shallow FZDZ	0	2	2	0
FZRA	0	0	0	3
Cloud (no SLD)	1	2	0	1

1997+1998	**None**	**Pockets**	**Band(s)**	**Solid**
Deep FZDZ	3	7	1	1
Shallow FZDZ	1	2	2	0
FZRA	0	1	0	4
Cloud (no SLD)	2	7	1	1

Table 4 – Number of cases where aircraft-observed microphysical observations aloft were matched to patterns on regional radar mosaics. None = no echo, pockets = irregular, pocketed echo, band(s) = regular, elongated echo, solid = widespread areas of continuous or nearly continuous echo.

F - BALLOON-BORNE SOUNDINGS AND NASA SLD SOUNDING STABILITY ANALYSIS

National Weather Service (NWS) and NCAR CLASS soundings provided forecasters with profiles of temperature, dew point, and winds at Cleveland (NCAR only, during limited periods) and several surrounding sites (e.g. Detroit, Wilmington, Pittsburgh, Buffalo) twice per day. Sounding data provided an excellent indication of the location, altitude and temperature of clouds and precipitation, as well as information on stability and winds. Such information was very useful for the identification of icing layers and, under certain conditions, SLD layers. However, their primary limitation was that their usefulness decreased with time after the launch and distance from the site, especially in areas of marked changes in atmospheric conditions (e.g. near fronts, mountainous terrain, and shorelines). NWS soundings were only launched at 0000 and 1200 UTC, 12 hours before and at the time of the morning briefing, respectively. The 1200 UTC soundings were not typically available until after the briefing, and 0000 UTC soundings were often so old that they were not of great value. Sounding data were of limited use without additional information from satellites, radars and surface observations, which provided the context of the sounding and indicated how applicable it was to the weather in the surrounding area.

The stability of the atmosphere can play a significant role in the development of the microphysical composition of clouds and precipitation, but the importance of stability in the production of SLD, especially via the CC process, is still unknown at this time. In an effort to shed some light on this subject, vertical profiles of temperature recorded during 25 Twin Otter encounters with SLD were examined. In the table below, the type of precipitation (FZDZ/FZRA encountered aloft), average change in T with height (dT/dz), layer depth, and comments are given for each SLD case. It is important to note that the lapse rates were for the SLD layer, itself, including any portion thereof that occurred below cloud base. It may have been more desirable to perform this analysis for the cloud deck that generated the SLD. However, the location of the generation zone was not easy to determine in many cases, because the aircraft did not sample a perfectly vertical profile, and issues of advection and tilting of the generation and observed SLD zones could come into play. Thus, the values shown here are representative of the lapse rates observed *within the observed SLD layer*, and may not be representative of the conditions necessary to generate the SLD. Cases are broken into two groups: those where CC was definitely the cause of FZDZ, and those where classical processes may have played a role.

Overall, the FZDZ cases formed by CC show lapse rates anywhere between isothermal (dT/dZ=0) and essentially moist adiabatic (dT/dZ ~ 2.0). Most cases were somewhat stable, with lapse rates that hovered between −1.0 and −1.5 C/kft, but several cases had lapse rates that were significantly more or less stable. For those cases with steeper (more negative, unstable) lapse rates, lake effect often played a role in the formation of the FZDZ. The more unstable cases sometimes featured FZDZ that was more intermittent in nature, and had smaller drop sizes. There were certainly exceptions, however. Classical cases typically had "gross" lapse rates of 0.0 C/kft, simply because the SLD layers started at the base of the warm nose, whereT=0C, and often ended where the temperature again reaches 0C. Lapse rates between these two freezing levels varied dramatically, but since the SLD is formed via the melting of snowflakes aloft, the lapse rates in the SLD layer are unlikely to be important to the SLD formation process.

Date	SLD Type	Lapse Rate (C/kft)	Depth (ft)	Mechanism & comments
970124	FZDZ	-1.1	5000	CC, mixed phase
970127	FZDZ	-1.0	2500	CC
970204	FZDZ	-1.9/-1.6	5000	CC, mixed phase, two soundings
970205	FZDZ	-1.5/-1.2	3.5-4.5k	CC, two soundings
970320	FZDZ	-0.7	2000	CC
971209	FZDZ	-0.1	5700	CC
971211	FZDZ	-1.8	2700	CC, mixed phase, lake effect, over YNG
980122	FZDZ	-1.8 (??)	1500	CC, below cloud, FZDZ extent into cloud not sampled due to horizontal movement of A/C, dT/dz > 0 just above.
980126	FZDZ	-1.8	2000	CC, intermittent, Sheboygan, mxd phs, F2
980126	FZDZ	-1.3	3400	CC, lake effect, -2.1 C/kft sfc to 2kft, F2
980126	FZDZ	-2.3	1700	CC, over Lake Michigan, lake influence/effect?
980127	FZDZ	-1.7	100-200	CC, very brief, shallow, mixed phase
980130	FZDZ	-2.3	1700	CC, lake effect, small/light FZDZ, mixed phs
980205	FZDZ	-1.1	5000	CC, FZDZ at 7-12kft, above warm nose, F1
980224	FZDZ	-1.3	7000	CC, intermittent, mixed phase
980227	FZDZ	-1.5	2000	CC, intermittent, mixed phase
980325	FZDZ	0.0	200	CC, brief
970115	FZRA	+2.1	2000	Classical
980112	FZDZ	-1.0	1400	CC and/or classical, could not determine
980204	FZRA	0.0	2.5-3.0k	Classical, PKB/ZZV/CAK, F1-F2-F3
980205	FZRA/FZDZ	0.0	2500	Classical and/or CC, below warm nose, F1
980205	FZRA	0.0	2000	Classical, F2
980219	FZDZ	0.0	1300	CC and/or classical
980320	FZRA	0.0	3000	Classical

Table 5 – Lapse rate derived from Twin Otter static temperature data within observed SLD layers. Precipitation types observed aloft, SLD layer depths, probable mechanisms, and relevant comments are indicated.

G - UPPER-AIR CHARTS

Upper-air charts show data from all regular sounding sites around the U.S., Canada, and Mexico at standard pressure levels (e.g. 850, 700, 500 mb). These data were useful for identifying features aloft which were/weren't conducive to the formation of icing and SLD. Some features of interest were 1) large-scale areas of saturated/dry air, 2) warm/cold temperature advection, 3) upper lows, troughs, ridges, and 4) warm/cold pockets of air. The locations of these features provided a large-scale perspective on the icing situation and indicated large-scale changes moving through the forecast area. However, upper-air charts were time consuming to analyze, were only available every 12 hours and the 1200 UTC plots were not available until well after the morning briefing. Also, the soundings used to make these charts were typically taken several hundred kilometers apart, and provided a relatively sparse dataset which was not adequate to sample the small-scale features which are important for icing.

UPPER-LEVEL CHART FEATURE						
1998	CAD w/LE	CAD w/o LE	WAD	ULOW	UTROF	TOTAL
Deep FZDZ	2	2	8	4	7	10
Shallow FZDZ	0	2	2	0	3	3
FZRA	0	2	3	2	2	3
No SLD	1	2	2	0	3	4
TOTAL	3	8	14	5	14	19
1997+1998	CAD w/LE	CAD w/o LE	WAD	ULOW	UTROF	TOTAL
Deep FZDZ	2	2	11	4	10	13
Shallow FZDZ	0	3	4	1	4	6
FZRA	0	2	5	2	4	5
No SLD	4	4	4	1	9	10
TOTAL	6	11	22	7	25	32

Table 6 – Number of cases where aircraft-observed microphysical observations aloft were matched to features on synoptic-scale upper-air charts. CAD = cold advection, WAD = warm advection, LE = lake effect, ULOW = upper low, UTROF = upper trough.

During the two flight seasons, SLD was observed in 6 of the 7 cases where areas close to upper lows were sampled, while upper troughs were present in most SLD cases. Of the 13 cases of deep FZDZ, 11 occurred with WAD, while only 4 were with CAD. Of those 4 CAD cases, 2 were not associated with significant LE. Among these two cases, one may have been a marginal LE case, and the other occurred on a sharp transition zone from CAD to WAD (it was counted in both categories, but could have been removed from either or both). Based upon this very small sample, when CAD was present, LE conditions may have been a key to the production of deep FZDZ. CAD with LE was not a good combination when cloud top temperatures were cold enough to result in snow, as in the 4 cases where no SLD was found. Overall, SLD was sampled in 82% of cases with WAD, yet only in 53% of cases with CAD. While those numbers are not staggering, WAD and CAD were present in 85% and 31% of deep FZDZ cases, respectively. WAD was also present in all 5 FZRA cases, while CAD was present during only 2 of them. Surface CAD was not considered here, and may have been present in some of the other FZRA cases since the lower subfreezing layers are typically at altitudes below 5000 feet (850 mb).

As seen in 1997, areas of SLD tended to occur with WAD, and near some semblance of upper level forcing, such as an upper-trough and/or upper-low. While these features provided some lift, the lift was typically fairly gradual in the FZDZ cases. Without the right combination of ingredients, however, the lift from these features resulted in small-drop icing at most (10 cases). Stronger, deeper lift was often found in the FZRA cases, and resulted in an efficient snow process aloft. Some SLD was associated with CAD, but not as frequently as with WAD, and for deep FZDZ to occur, it appears that LE conditions may have

been important. CAD was often necessary to maintain the cold air layer beneath the melting zone for FZRA, and provided a cold dome over which the warm air was lifted.

H – COMPUTER MODEL OUTPUT

National Center for Environmental Prediction computer forecast models provided forecasters with gridded 3-D forecasts of the structure of the atmosphere over the U.S., Canada and Mexico. Forecast fields of temperature (T), relative humidity (RH), surface pressure, and precipitation from the Rapid Update Cycle (RUC) and Eta models were used to predict changes in the structure of the atmosphere and their effect on icing and SLD potential in the 3-12 hour (RUC) and 12-48 hour (Eta) time frames. The models did a very good job at capturing the general locations of the primary surface (lows, highs, fronts, precipitation) and upper-air (lows, troughs, jets) features, but often did not provide adequate information on the nuances in the T and RH fields which are important for icing and SLD, especially FZDZ.

The models sometimes had difficultly resolving low-level cold pools, sharp transition zones, and the effects of the Great Lakes (mesoscale), topography of the Appalachians, and snow cover. These shortcomings have led to significant errors in the depth and temperature of clouds and precipitation that, in turn, led to major differences in the potential for icing and SLD. Overall, the models provided very useful general information on the large-scale conditions that could be expected in the 3-48 hour time frame, but the fine-scale details, which are critical for the forecasting of icing and SLD, could not be taken at face value.

I - NCAR IN-FLIGHT ICING ALGORTIHMS

As described in the report released following the 1997 flight season, in-flight icing algorithms were not particularly useful for forecasting the fine-scale details necessary for NASA's SLD flight operations. Icing algorithms based upon national-scale models alone (e.g. RAP), and combinations of this information with observations from surface stations (Stovepipe) were designed for identifying icing on a larger scale. Forecasting for NASA further heightened our awareness of the importance of combining information from several data sources for producing high-quality diagnoses and forecasts of icing. Each data source provided valuable information, but none could stand alone.

While model output provided a three-dimensional picture of the atmosphere (temperature, relative humidity, height, etc.) that was relatively accurate on the large-scale, fine details important for aircraft icing were often not adequately resolved. This was especially so for identification of cloud decks using the relative humidity field. It was difficult for the models to accurately depict cloud top height, cloud base height, breaks between cloud decks, temperatures within cloud decks, and actual cloud extent. These errors sometimes resulted in critical differences in the expected microphysics within the cloud. Good quality measurements of the cloud top temperature and other measurements frequently gathered from satellites provided a good first guess at the microphysical makeup of tops of the highest clouds. However, this information only applied to the highest cloud deck, and lower cloud decks and layers that contain significant icing were sometimes hidden from the satellite.

Cloud top temperature may be used in combination with model-based temperature profiles to roughly determine the cloud top height. Cloud base height, as well as the occurrence of precipitation and its type, can be gathered from surface observations. However, surface stations were not regularly spaced, and all observation platforms are not the same. Thus, interpolation schemes were used to fill in data gaps between stations, and methods were developed to handle the differences in surface precipitation measurements. Radar mosaics provided much finer detail regarding the locations of precipitation, filling in the gaps between surface observations, and alerting forecasters as to the intensity of the precipitation. However, the radar mosaic could not determine precipitation type, was rather insensitive to light precipitation (especially freezing drizzle, drizzle, and light snow), and had problems with blockage and coverage in mountainous regions. Each data set provided critical details regarding the nature of the clouds and precipitation, but without using this information in concert, one could not accurately assess which microphysical processes were occurring. This was essentially the approach that NCAR forecasters used to manually determine the locations of icing and SLD for NASA. Following the 1997 season, the integrated icing diagnostic algorithm (IIDA) was developed to mimic this approach, and improve upon icing algorithms that were either entirely model- or observation-based.

IIDA development was complete before the 1997-98 NASA flight season, but was still somewhat experimental at that time. NCAR forecasters regularly monitored the output, comparing it with actual observations from the research aircraft and other sources, but did not use it as a primary forecasting tool for the project. Verification of IIDA was completed using icing PIREPs from across the country for the period encompassing the flight season (Brown et al., 1999 - see attached). Results were very encouraging, and showed that IIDA was superior to other algorithms at detecting icing PIREPs while it minimized the airspace warned. While these results are quite valid, limitations of the PIREP verification database have been well documented, including its subjective nature, and possible discrepancies in location, time, and decoding. More direct measurements of the atmosphere made by the NASA Twin Otter can be used to better determine the horizontal and vertical extent of supercooled liquid water and SLD for comparison with IIDA. This verification method also has drawbacks, including limited geographic coverage (lower Great Lakes region only), the lack of random sampling (flights were intended to find SLD and icing), and the flight locations were determined using similar techniques to those used to develop the algorithm. However, if the techniques were not of good quality, then the aircraft would not have encountered SLD and/or icing, and the verification of an algorithm based on this approach would show its inabilities. Flight time was evenly split between "icing" and "non-icing" periods, so there was a nice amount of verification data for both events and non-events.

For the 1997-98 flight season algorithm runs, IIDA was run on the Rapid Update Cycle version 1 (RUC), with roughly 60-km horizontal resolution. The minute-by-minute location of the aircraft was used to identify the four RUC grid points which immediately surrounded it, then the altitude range covered was used to find all vertical grid points that were within 1000 feet (305m) of the aircraft. This vertical verification window was used due to irregular vertical spacing of the model grid points. Results from these analyses tell us how well the IIDA depicted icing and SLD within 1000 feet vertically, and one grid point

horizontally. One can think of the verification points as a 3-D box of space that surrounds the aircraft at any given minute. IIDA icing and SLD "potential" floating point values between 0.00 (no icing/SLD potential) and 1.00 (very high icing/SLD potential) were calculated for every grid point across the U.S. and southern Canada, including the Great Lakes. The one exception is that a value of -9.9 ("unknown") was assigned to the SLD field if no information was available that allowed the algorithm to determine an SLD potential using the techniques currently employed. For a full description of how the IIDA determined icing and SLD potential, see McDonough and Bernstein (1999 - attached). This verification was performed by determining the maximum and minimum values of icing and SLD potential within the box surrounding the aircraft, and comparing it to the icing and SLD confidence levels for that minute. Since IIDA calculates floating point values, a distribution of the number of times each range of values of icing and SLD potential was matched to each confidence rating was developed (see Table 7). Some brief, pertinent results will be discussed here.

Note that because of the speed of the aircraft and the spacing of the RUC model grid points, several minutes of aircraft data may have been matched to the same RUC points, and thus, IIDA output values. Using a typical ground speed of 120 knots (60 ms^{-1}), it takes the Twin Otter about 17 minutes to cover 60km of distance, or one grid point. Changes in altitude can also bring about matches with different vertical grid points within the same horizontal location. This worked both in favor and against the algorithm. If IIDA did a particularly good or bad job at a given grid point, then the good/poor values were counted in the verification several times. Overall, more than 3100 minutes (52+ hours) of aircraft data was compared to IIDA, and more than 1000 horizontal grid points verified. A total of 17 out of the 19 flight days were verified. No data were available for 980112 and 980129, as well as the hours between 15 and 17 UTC on 980318. For each horizontal grid point, several vertical grid points were typically tested. Also, the sampled conditions and resulting icing and SLD confidence values can vary significantly from minute to minute. Thus, despite the fact that some redundancy is inherent in this dataset, the sample size is still large.

Overall, the results were quite favorable. When comparing the maximum icing values within the verification box to those times with ICE-3 (highest confidence that icing was occurring - 910 minutes), no occurrence was ever missed (ICPOT was never 0.0). Low potentials (<0.2) were very rare (1% of the time), the potential for icing was at least moderate (>0.5) 92% of the time, and was very high (>0.9) 36% of the time (see Table 7). Thus, IIDA did a very good job of identifying times when icing was present. However, an algorithm can do this by simply saying "yes icing" or "high potential" all of the time - a gross over warning. It is equally important to minimize the amount of airspace warned and to correctly identify those times when icing does NOT occur. When IIDA indicated that the maximum icing potential within a box was >0.9, the aircraft definitely had icing 36% of the time, and probably encountered it (ICE-1, -2, or -3) 66% of the time. When all of the grid points within the box (maxval) had ICPOT=0.0, the aircraft definitely had no icing (ICE-0) 94% of the time, ICE-1 or -2 about 6% of the time, and never had ICE-3 (163 total minutes tested). Also, of the 1496 minutes when no icing was indicated (ICE-0), grid points with ICPOT=0.0 and ICPOT<0.2 were present somewhere within the box (minval) 35% and 62% of the time, respectively. The ability of IIDA to identify locations with no icing and to differentiate between areas of

"icing" and "no icing" appears to be good. The results are especially good when the high variability of conditions sampled within a roughly 60km by 60km box are considered. The difference between icing and no icing within such an area is strongly dependent upon encounters with discontinuous clouds, relatively thin breaks between cloud layers, pockets of water and ice crystals, as well as gradients in temperature both horizontally and vertically across fronts, terrain, and water/land boundaries.

SLD results were rather interesting. Overall, there were 578 minutes with a high confidence that SLD was present (SLD-3). Of those times, IIDA was unable to determine an SLD potential (SLDPOT = -9.9) 28% of the time, and incorrectly produced an SLDPOT=0.0 only 1% of the time. Thus, the IIDA SLD technique was able to correctly identify some potential for SLD (SLDPOT>0.0) 71% of the time that SLD was likely to have been observed. Also, of the times that IIDA had adequate information to calculate an SLDPOT (values of -9.9 / "unknown" were not counted against IIDA), and SLD-3 (high confidence) was present, maximum values of at least moderate (>0.5) and high (>0.9) SLD potential were indicated within the box 90% and a remarkable 71% of the time, respectively. Again, however, it is important not to overwarn. When the Twin Otter data showed no indication of SLD (SLD-0.0, 1656 minutes), IIDA indicated "no SLD" (potential of 0.0) for the minimum and maximum within the box (minval/maxval) about 31% and 25% of the time. These results improved to 60% and 42% when only those locations where a potential was calculated were considered (values of -9.9 excluded). Values of -9.9 completely filled the box 41% of the time, meaning that no SLD indicators were present, not that IIDA indicated that there was no potential for SLD in the box. When IIDA did predict SLD potentials of 0.00 throughout the entire box (maxval) surrounding the aircraft (443 points), the aircraft only observed likely SLD (SLD-3) 1% of the time. As was the case for icing, we see that IIDA shows good ability to differentiate between areas of SLD and no SLD.

Of course, there is a down side to these statistics as well. Of the times that no icing was observed by the aircraft (1496 minutes), high icing potentials (>0.9) were calculated for at least 1 point within the box (maxval) 21% of the time, and for every point within the box (minval) 4% of the time. Moderately high icing potentials (>0.7) were similarly found 51% and 18% of the time, respectively. This clearly represents some overwarning, but a good portion of this overwarning may be attributable to meteorological variability within a given set of 4 RUC grid points. When no SLD appeared to be present (SLD-0) and SLD potentials were calculated (923 minutes), high SLD potentials (>0.9) were present 16% (at least 1 point - maxval) and 0.1% (all points - minval) of the time, while moderately high SLD potentials (>0.7) were present 28% and 5% of the time, respectively. Overwarning is still a bit of an issue for the SLD field, but does not appear to be serious. Brown et al. (1999) showed that, on average, the IIDA SLD field only warned roughly 1% of the U.S. volume of airspace.

Maxval	0.0	0.09	0.19	0.29	0.39	0.49	0.59	0.69	0.79	0.89	0.99	Total
Icing-0	154	63	105	169	48	43	72	76	135	323	308	1496
Icing-1	1	8	15	33	7	21	22	51	96	175	214	643
Icing-2	8	0	2	2	1	2	3	2	5	14	49	88
Icing-3	0	3	7	22	15	23	35	76	179	224	326	910

Minval	0.0	0.09	0.19	0.29	0.39	0.49	0.59	0.69	0.79	0.89	0.99	Total
Icing-0	519	215	199	39	45	68	58	78	108	110	57	1496
Icing-1	83	112	60	30	36	22	57	70	83	55	35	643
Icing-2	18	14	6	9	2	0	0	27	8	3	1	88
Icing-3	75	122	74	72	34	78	123	126	104	78	24	910

Maxval	-9.9	0.0	0.09	0.19	0.29	0.39	0.49	0.59	0.69	0.79	0.89	0.99	Total
SLD-0	653	390	68	69	27	26	34	29	18	46	67	149	1576
SLD-1	470	43	14	45	26	11	31	12	10	11	27	93	793
SLD-2	42	4	0	1	2	0	0	0	0	0	1	1	51
SLD-3	164	6	7	9	4	2	15	3	23	20	33	292	578

Minval	-9.9	0.0	0.09	0.19	0.29	0.39	0.49	0.59	0.69	0.79	0.89	0.99	Total
SLD-0	762	489	62	64	26	62	19	12	36	13	30	1	1576
SLD-1	500	49	37	62	49	18	16	6	14	16	10	16	793
SLD-2	44	4	0	1	0	0	0	0	0	0	2	0	51
SLD-3	193	46	67	15	44	9	3	29	45	66	55	6	578

Table 7 – Number of minutes where IIDA icing and SLD potentials (columns) were matched to aircraft-observed icing and SLD confidences aloft (rows). Maxval = maximum, minval = minimum IIDA icing/SLD potential value of all grid points tested.

Stratification of the results into periods when the aircraft was in the altitude ranges of 0-5000 feet, 5000-10000 feet, and >10000 feet MSL revealed that IIDA's performance varies somewhat with altitude. In general, verification results for the icing field were best in the lowest 5000 feet, and gradually decreased with increasing altitude. The main trend was that the ICE-3 cases shifted from the highest potentials to more moderate ones (0.5 to 0.89) with increasing height. Determination of "no icing" was also better at lower altitudes, in general. The SLD field did a much better job of identifying high SLD potentials when SLD was definitely present (SLD-3) in the lowest 5000 feet (the SLD potential was >0.7 and >0.9 about 75% and 66% of the time, respectively). In the 5000-10000 foot altitude range, about 58% of SLD (99% when "unknown" values were excluded) was still associated with some SLD potential, with 31% (51%) having an

SLD potential of 0.5 or greater, and 41% falling into the "unknown" category (-9.9). Very little SLD-3 (25 minutes) occurred above 10,000 feet, with 72% falling into the "unknown" category, and the remaining 28% with very low SLD potentials of 0.01-0.09. Since surface observations of certain precipitation categories are very important to the calculation of an SLD potential, and surface information becomes less relevant with increasing altitude above cloud base, IIDA scales back the potential for SLD accordingly. This tends to results in rather low SLD potentials above 10,000 feet. The SLD-0 verification was good at all altitudes, but best below 5,000 feet as well.

The strong influence of surface-based cloud cover and precipitation information on the IIDA icing and SLD fields is borne out in these results. The extra information provide a clearer picture of the atmospheric structure and microphysical characteristics of the lower atmosphere. With increasing altitude, IIDA becomes more dependent upon model fields for these determinations. Despite valuable information from the GOES-8 satellite, IIDA must still rely on the accuracy of the RUC-model temperature field to accurately determine cloud top height from the GOES-8 infrared temperature, and the existence of multiple cloud decks from RUC relative humidity fields. Cloud top heights are quite difficult to determine, and thus, a conservative IIDA approach often leads to overestimating their height, further resulting in overforecasting of icing and SLD near cloud top. Poor identification of multiple cloud layers causes an underestimation of the icing and SLD potential because IIDA calculates low potentials based upon indications of a continuous cloud layer with cold tops, where ice crystals rather than supercooled liquid water droplets, are likely.

J - PILOT REPORTS (PIREPs)

Past research has shown that environments that were likely to have significant liquid water contents and/or SLD were associated with an unusually large percentage of PIREPs that had both moderate or greater intensity and mixed or clear type. These findings made intuitive sense, and such PIREPs were used as a clue in the search for SLD, especially when surface observations, satellite data, and/or upper-air features were not present or available to forecasters (e.g. due to data outages).

To examine the usefulness of these PIREPs as a tool for finding SLD, the PIREPs in the vicinity of the 1998 flights were cataloged. Results from 1997 bore out that significant LWC (> 0.3 gm^{-3}) was often present, but that SLD was only present some of the time. It was concluded that these PIREPs should be used primarily as a confirmation that significant LWC is likely to exist and that the potential for SLD is somewhat higher than in clouds that were not associated with these PIREPs. Similar results were found for the 1998 flights, where such PIREPs were present in nearly every case flown, whether or not the Twin Otter sampled SLD. They were not present in one SLD case where the FZDZ was all at T>-3C and the LWC was low. The only other case where they were not present was one with brief, shallow FZDZ. Other subdivisions of PIREP icing severity and type (e.g. moderate or greater rime icing, any icing) examined showed no skill in differentiating between small-drop clouds and SLD situations.

K - IN-FLIGHT FEEDBACK FROM NASA

Real-time feedback from the NASA crew via SATCOM remained one of the most critical pieces of information for finding SLD. An excellent example of this is the 980204 Parkersburg WV case. Initially, the aircraft was advised to search for possible pockets of FZDZ above 7000 ft, and found nothing. The reports that the clouds were composed entirely of ice crystals, combined with new weather observations and PIREPs not available before initial takeoff, signaled a change in strategy and led to subsequent flights into FZRA below 3000 ft along the Ohio-West Virginia border. Without real-time communications, we would have missed this important event. Similar decisions and fine-tuning of initial forecast SLD locations have proven to be critical for successfully finding, remaining within, and thoroughly sampling SLD. Verbal descriptions of the vertical and horizontal structures of the clouds and precipitation provided forecasters with high-quality, real-time feedback on the flight environment and the success of the most recent forecast or in-flight guidance. Information on the height of cloud top, dry layers and freezing levels was also critical for properly identifying escape routes.

As in 1997, the primary limitation to in-flight feedback was that the aircraft only provided information for small area at a given time, rather than across the entire region. Both forecasters and on-board researchers can be fooled by such local-scale information, leading to mistakes in short-term planning and sampling. One must keep the big picture in mind while examining the small picture they either see before them or hear about via the SATCOM.

3. An assessment of NCAR forecaster performance during the 1998 season.

This section is intended to provide a brief summary of the NCAR icing and SLD forecasts, an assessment of the failure points of the forecasting process, and some suggested changes in forecasting techniques for future flight seasons. During the 19 cases that NASA sampled, the following phenomena were forecast and sampled:

Overall, icing was again found in every case where the Twin Otter was dispatched for icing studies. In 6 of the 7 cases where deep layers of FZDZ were predicted to be likely, FZDZ was observed either through a continuous deep layer or at altitudes covering a range of at least 2km. In one case, no SLD was observed. These cases represent those where the forecasters were particularly confident that FZDZ would be found aloft, and that it would exist through an extensive range of altitudes.

The forecast category of "possible pockets of FZDZ" represents those cases where the forecasters were confident that icing would exist, thought that conditions were ripe for FZDZ to be found in pockets aloft, but were not confident that it would be found through extensive altitude ranges. The variety of weather observed in these 11 cases (4 deep FZDZ, 3 pockets/shallow FZDZ, 1 ZR, 3 no SLD) shows that SLD was typically found (72.7% of the time), but that it came in a variety of forms and depths.

When FZRA was predicted, FZRA was found in both cases. FZRA forecasts are relatively easy compared to FZDZ forecasts. Clues for FZRA in sounding data, surface observations, computer model and IIDA output are often quite obvious. In one case where FZRA was observed by the aircraft (980204), FZRA was not discussed in the forecaster notes. In this case, forecasters focused too strongly on the mild potential for FZDZ in pockets of warm CTTs above the warm nose, and not on the potential for FZRA to the south. FZRA bust flights from the 1997 season shied forecasters away from directing the Twin Otter into FZRA, unless it was significantly deep and cold for good sampling and icing potential. The FZRA sampling on this flight did not begin until the potential FZDZ aloft was a bust (CTTs were too cold), the signatures for FZRA became more obvious, and a single PIREP showed good icing potential in the FZRA layer along the Ohio-West Virginia border. It ended up being the best FZRA case sampled during the two seasons.

Of the 19 days with icing research flight data, SLD was observed during 15 of them, and icing was encountered during every case. A total of 46 flights were made during the season, some of which were simply "ferry flights" to or from the SLD target area. Of the 40 flights made where quality 2D-grey data were available, "significant SLD" was found on 11 of them (28%), and "marginal SLD" on 13 more, according to an initial analysis done by NASA Glenn's Dean Miller. In that analysis, SLD information was not available for 980320 (4 flights) or 980325 (2 flights) due to 2D-Grey problems. According to flight notes from those days, SLD was observed during 3 of the flights on 980320, and during the first flight on 980325. Overall, SLD was found on 28 of the 46 flights made (61%). "Significant SLD" was likely present during the first three flights on 980320, and neither of the 980325 flights, bringing the overall, rough total to 14 out of 46 flights (30%).

These results are comparable to those from 1997 (29% of flights had "significant SLD", and 54% had at least some SLD). However, the approximate number of minutes of flight spent in "significant"

(237 in 1997 vs. 600 in 1998) and "marginal" (65 in 1997 vs. 190 in 1998) SLD, and the approximate percentage of flight time spent in "significant" (9% in 1997 vs. in 16% 1998), "marginal" (2% in 1997 vs. 5% in 1998) and any (11% in 1997 vs. 22% in 1998) SLD (not including flights from 970325, 980320, and 980325, since SLD minutes could not be determined) increased significantly. The percentage of flight time spent in any, and "significant" SLD conditions roughly increased by 100% and 75% in 1998, compared to 1997. This improvement appears to indicate an increase in forecasting and in-flight guidance skill over the previous season. Also, the fact that NASA was able to find SLD more than 1 out of every 5 minutes of flight time in 1998 causes one to question the tag of "rare" that is often applied to SLD conditions.

		OBSERVED SLD OCCURRENCES ALOFT				
	1998	Deep FZDZ, or FZDZ through >2km range	Pockets of, or shallow FZDZ	FZRA	No SLD	Total
FORECASTS	Deep FZDZ	6	0	0	1	7
	Possible pockets - FZDZ	4	3	1	3	11
	FZRA	0	0	2	0	2
	Total	10	3	3	4	19

Table 8 – Number of cases where SLD forecasts were matched to aircraft-observed SLD occurrences.

As in 1997, the success rate of the forecasts was good, but there is room for improvement. Our techniques worked fairly well, but they need some refining and we need additional practical experience with their application for forecasting. The main failure points of the forecast process are:

A – After being burned by flying FZRA cases that were not cold or deep enough for good icing flights in 1997, we shied away from FZRA cases too quickly in 1998. This was clearly demonstrated by not going initially for FZRA on 980204, as well as for two other reachable events at Alpena MI and Syracuse NY. Both of the latter events would have made valuable additions to the FZRA database, since they had rather cold (T < -5C) FZRA layers. We should be more aware of FZRA cases, and continue to be cognizant of how "flyable" the icing is in each case, so that we don't attempt to sample FZRA layers that are too warm and/or shallow (e.g. 980205).

B – Successful long distance "chases" for SLD, and especially FZRA, are certainly possible (e.g. Green Bay,WI on 980126, Indianapolis IN on 970115, Battle Creek MI on 980320, and Parkersburg WV on 980204). Forecasters must be able to identify situations where the icing and SLD are expected to be long-lived if they currently exist, or where conditions are very likely to form and maintain themselves. To make such long missions worthwhile, prolonged, significant SLD must be very likely. Outside of the Indianapolis case, we have not taken advantage of pre-positioning the aircraft for flights on the following

day. One case where we could have done this effectively was an overnight at Green Bay following the 980126 flights. FZDZ conditions were again present on the morning on 980127. Forecasters did not identify this situation, and perhaps it was not an obvious one. FZDZ is *very* difficult to predict beyond the 3-hour time frame, and an 18+ hour forecast is probably beyond our abilities. Such a forecast would have been required to capture the FZDZ at Green Bay on 980127.

C – "A bird in the hand is worth two in the bush." This sometimes applies well for SLD forecasting. As forecasters, we determine where SLD is likely and tend to focus on that location from then on. In cases where SLD is encountered along the way to that location, we should give serious consideration to sampling those conditions further before proceeding to the forecasted SLD site. At times, we have missed some (or did not fully explore) potentially good SLD sampling opportunities because of this (e.g. near Toledo on 980129, Zanesville on 980205), and in other cases, we were correct to press on s to find "better" SLD conditions at the target site (e.g. Green Bay on 980126, Saginaw MI on 980227).

D – Air source may be an important consideration for FZDZ cases, as we have expected. Elevated layers of cloud that are removed from dirty, surface-based air sources loaded with cloud condensation nuclei and ice nuclei may be particularly good sites for FZDZ growth, given other important factors (sufficient LWC, cloud depth, lack of seeding from aloft, etc.). Clean low-level air sources, like air that has blown across long fetches of one of the Great Lakes, can bring clean surface-based air into a cloud. Lake effect FZDZ cases (e.g. 971211 at Youngstown, 980126 at Green Bay), and past climatology studies seem to point to this.

E – The value of certain datasets should not be underestimated. With a briefing time of 1200 UTC, several key datasets are often not available. In particular, balloon-borne soundings from the National Weather service are typically not available until about 1300 UTC, mid-winter visible satellite data is of limited value until at least 1300 UTC, and very few PIREPs are made before 1400 UTC. While forecasters can get a good idea of the meteorology and the likelihood of SLD, these three datasets provide important information that shape and refine the forecast (e.g. cloud structure and thickness, consistency/variability, robustness/confirmation of the icing). Many times, we have enough information to say "go" at briefing time, and this provides the advantage of beating the rush at Cleveland Hopkins Airport. In some cases, however, conditions are more fleeting or not as good as we thought, as borne out by the new data that comes in after the "go" is given. Resources are used ineffectively because the crew either ends up sampling marginal conditions, or comes home having not sampled any SLD. It's a tricky game, since SLD conditions are often at their best in the early morning, yet our information is at its poorest at that time. If we wait for more information, we can make a better decision about the likelihood of SLD, but the conditions may be waning, if not gone.

Table 9. Weather features, SLD and icing forecasts and Twin Otter observations for 1998 icing research flight days.

Date	Freezing Drizzle	Freezing Rain	Ice Pellets	Drizzle	Rain	Snow	Overcast	Cold Front	Warm Front	Stationary Front	Occluded Front	Surface Trough	Lake Effect	Surface Low Center	Upper Low Center	Upper Trough	Warm Advection	Cold Advection	Maximum CTT	Minimum CTT	Radar Echo Pattern	Trace to Light Icing	MOD+ Rime Icing	MOD+ Mixed/Clear Icing	SLD Forecast	Icing Forecast	SLD Observed	ICING Observed	Maximum LWC at T < 0 C	Forecast sheet / Notes	Comments
971209	X			X		X	X					X				X	X		-10	-15	Pockets	X		X	ZL: Sfc-6k, 7-11k	0-6k, 7-11k	ZL: 1.3-6.0k	1.3-7.2k, 10.2-11.4k	0.3	FS	Warm ZL and icing predicted & found below 6k. Dry layer 7.2-10.2k. Sfc ZL observed 50-100km to the SW.
971211	X	X		X	X	X	X					X	X	X	X	X	X	X	-10	-16	Pockets	X	X	X	ZL: Sfc-11.5k	Sfc-11.5k	ZL: Sfc-4k, some at 9.2k	Sfc-8k, 9.2-11.5k	0.75	FS	Weak surface low. Two cloud decks, both had icing.
980112	X	X		X	X		X	X	X							X	X		-7	-20	Pockets	X	X	X	ZL: Sfc-8k	Sfc-10k	ZL:Sfc-3k	Sfc-3k, 6-12k	0.7	FS	Ahead of cold front, south of WF. T>0C 3-6k, ZL from CC and/or melting
980122	X					X	X					X			X	X	X		-15	-15	Solid early, pockets late	X	X	X	Possible pockets of ZL: Sfc-12k	Sfc-12k	ZL: Sfc-2.7k, 6.0-6.5k	Sfc-5k, 9-12.5k	0.25	No	ZL & graupel observed @ CLE by BB/FM. Multiple decks. Mixed conditions in ZL.
980126	X					X	X			X		X	X			X	X		-10	-20	Pockets most of time, none late	X	X	X	ZL: Sfc-10k @GRB	Up to 13k, but sfc-10k @GRB	ZL: Most sfc-4k, patches 7-10k	Sfc-11k	0.6	No	Most CTTs near –15C @GRB.
980127						X	X		X			X				X	X		-5	-15	Pockets early, none late	X			Possible pockets of ZL: 2.5-10k	2.5-10k	ZL: 6.5-6.7k	3.7-7.0k	0.35	No	South of warm front, E of sfc trough. Looking for gaps in cold tops, along edges of precip

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Date	Freezing Drizzle	Freezing Rain	Ice Pellets	Drizzle	Rain	Snow	Overcast	Cold Front	Warm Front	Stationary Front	Occluded Front	Surface Trough	Lake Effect	Surface Low Center	Upper Low Center	Upper Trough	Warm Advection	Cold Advection	Maximum CTT	Minimum CTT	Radar Echo Pattern	Trace to Light Icing	MOD+ Rime Icing	MOD+ Mixed/Clear Icing	SLD Forecast	Icing Forecast	SLD Observed	ICING Observed	Maximum LWC at T < 0 C	Forecast sheet / Notes	Comments
980129	X			X	X	X	X	X				X		X		X		X	-5	-20	Pretty solid band	X	X	X	Possible pockets of ZL: 2-12k	2-12k	ZL: 6.5-7.2k	5-8.8k	0.3	No	Little info in notes, so reconstructed conservative forecast with FM. Behind cold front, SW of surface low
980130					X	X	X			X			X			X		X	-10	-15	None	X	X	X	ZL: sfc-6k	Sfc-6k	ZL: sfc-3k	Sfc-5.8k	0.8	No	Good notes with well-defined cloud top and sfc ZL noted. ZL was small. Stationary front to the north.
980204		X			X	X	X			X						X	X	X	-30	-50	Solid S, patchy / none N	X	X	X	Possible pockets of ZL 7-14k	1-14k	ZR: 1-4k	1-4k, 7-12k	0.25	No	Stationary front to SE, upper trough to E, cold advection below 850mb. Mixed cond's above 7k N end, snow above 7k @PKB. Layer clouds N
980205		X					X					X			X		X		-30	-50	Pretty solid, but some holes	X		X	ZR: Sfc-3.5k, possible ZL 6-12k	Sfc-3.5k, 6-12k	ZR & ZL: sfc-4.3k, ZL near 7k	Sfc-4.3k, 6.5-11k	0.2	No	Surface trough to the SW, upper low to the S. Layers of cloud above 10k.
980212					X		X	X				X				X		X	-5	-10	None	X	X	X	Possible pockets of ZL 2-12k	2-12k	Little/none, but possibly a few ZL drops	2.4-5.0k	0.5	No	Ahead of cold front. Better SLD chances in SW Ohio, but went N to try to fly coord mission with AES.

Table 9. Weather features, SLD and icing forecasts and Twin Otter observations for 1998 icing research flight days.

Date	Freezing Drizzle	Freezing Rain	Ice Pellets	Drizzle	Rain	Snow	Overcast	Cold Front	Warm Front	Stationary Front	Occluded Front	Surface Trough	Lake Effect	Surface Low Center	Upper Low Center	Upper Trough	Warm Advection	Cold Advection	Maximum CTT	Minimum CTT	Radar Echo Pattern	Trace to Light Icing	MOD+ Rime Icing	MOD+ Mixed/Clear Icing	SLD Forecast	Icing Forecast	SLD Observed	ICING Observed	Maximum LWC at T < 0 C	Forecast sheet / Notes	Comments
980219					X		X					X			X	X		X	-10	-25	None	X		X	ZL: 2-10k	2-10k	ZL: 2.4-5.6k, possible ZL ~9k	2.4-11k	0.8	FS	Upper-low to N and NE, dry layer 5.6-9.2k.
980224			X	X	X		X	X							X	X	X	X	-10	-20	Solid band	X	X	X	Possible ZL 5-10k	5-15k	Some ZL at 3.8k and 8k	4.5-10.5k	0.45	FS	Ice pellets to SW & S, upper trough to NE, ahead of cold front, weak warm advection @850mb, cold advection @700mb. Best, brief ZL at leading edge of precip shield.
980227					X	X	X				X				X	X	X	X	-8	-40	Solid band early, pockets late	X	X	X	Possible pockets of ZL 8-15k	8-15k	ZL 12-14.4k	9.3-14.9k	1.2	No	Transitioning from warm to cold advection. ZL in narrow band on back side of precipitation swath.
980302				X	X	X	X					X			X	X		X	-10	-20	Pockets	X	X	X	ZL: 3-12k	3-12k	None	2-13k	0.3	FS	Drizzle & sfc trough to NE, upper trough to NW. Only MOD+ mxd/clr icing PIREP to NW between flights. Mixed phase, small drop, and snow.

Table 9. Weather features, SLD and icing forecasts and Twin Otter observations for 1998 icing research flight days.

Feature	980305	980318	980320	980325
Freezing Drizzle				
Freezing Rain			X	
Ice Pellets				
Drizzle		X	X	
Rain		X	X	X
Snow	X		X	
Overcast	X	X	X	X
Cold Front				
Warm Front				X
Stationary Front			X	
Occluded Front		X		
Surface Trough	X	X	X	
Lake Effect	X			
Surface Low Center			X	
Upper Low Center			X	
Upper Trough	X	X	X	
Warm Advection		X	X	X
Cold Advection	X		X	
Maximum CTT	-12	-15	-20	-5
Minimum CTT	-15	-50	-50	-25
Radar Echo Pattern	Pockets	Mostly solid, some pockets	Solid nearly the whole time	Pockets early, none late
Trace to Light Icing	X	X	X	X
MOD+ Rime Icing	X	X	X	X
MOD+ Mixed/Clear Icing	X	X	X	
SLD Forecast	Possible pockets of ZL sfc-10k	Possible pockets of ZL 7-10k	ZR: sfc-5.5	Possible pockets of ZL 10-16k
Icing Forecast	Sfc-10k	7-15k	Sfc-5.5	10-16k
SLD Observed	None	None	ZR: sfc-5k	ZL: 7-9k
ICING Observed	2.5-6.6	8.3-12k	Sfc-7k	7-12k
Maximum LWC at T < 0 C	0.6	0.4	0.5	0.3
Forecast sheet / Notes	FS	No	No	FS
Comments	Surface trough well to S has no effect on case. Lake effect is weak. Dying upper trough, weak warm advection moving E, cold advection on W edge of area. Small drop, mixed phase. Breaks in clouds.	Surface trough just to the north. Looking for pockets in deeper clouds, and along back edge of precip.	Surface front to SE, surface trough and low to S, upper-low to S. T down to -5C in ZR	Warm front to the southwest. Very warm (T>3C), light, patchy ZL.

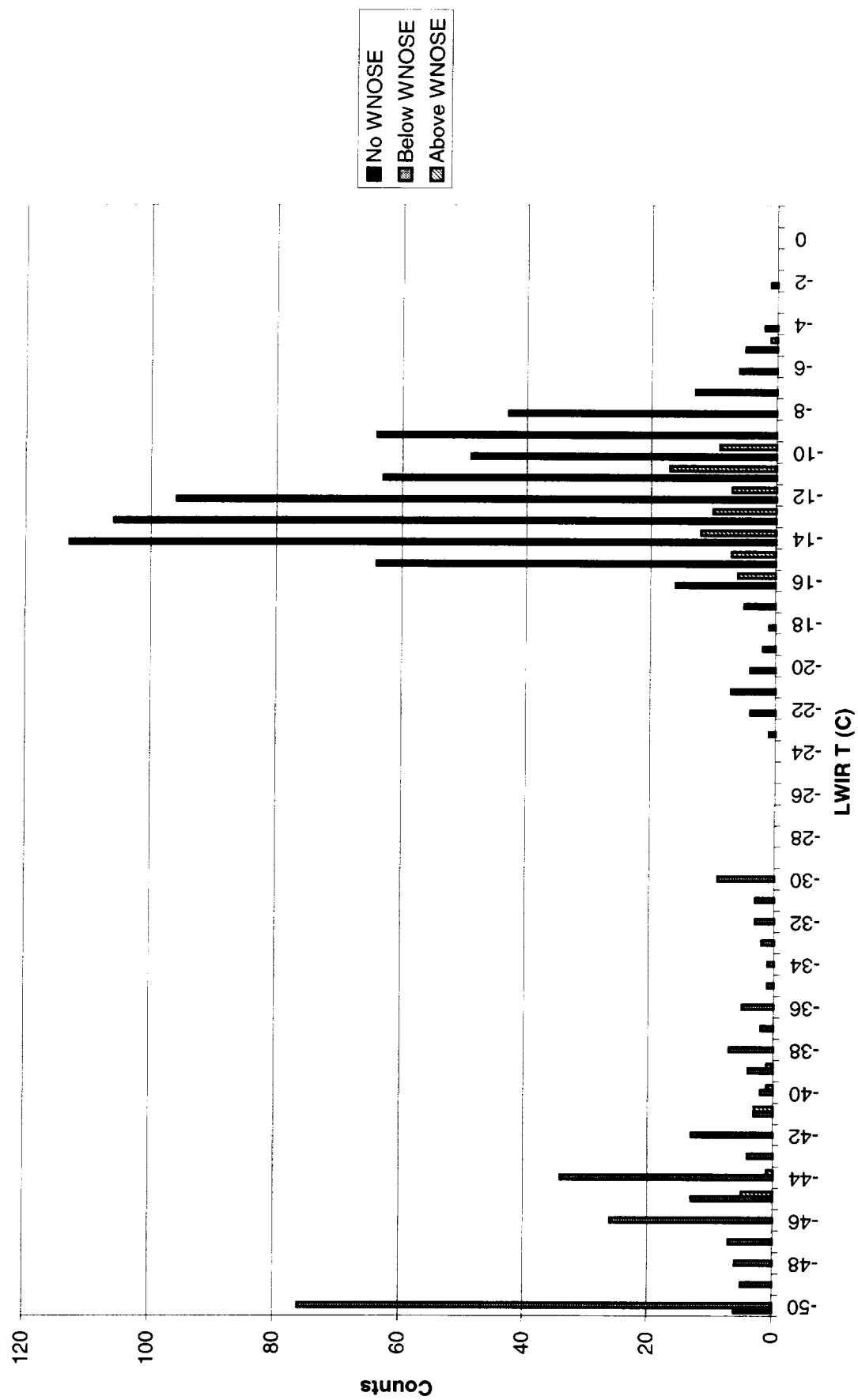Figure 1a - Mean LWIR Temps for ICE-3
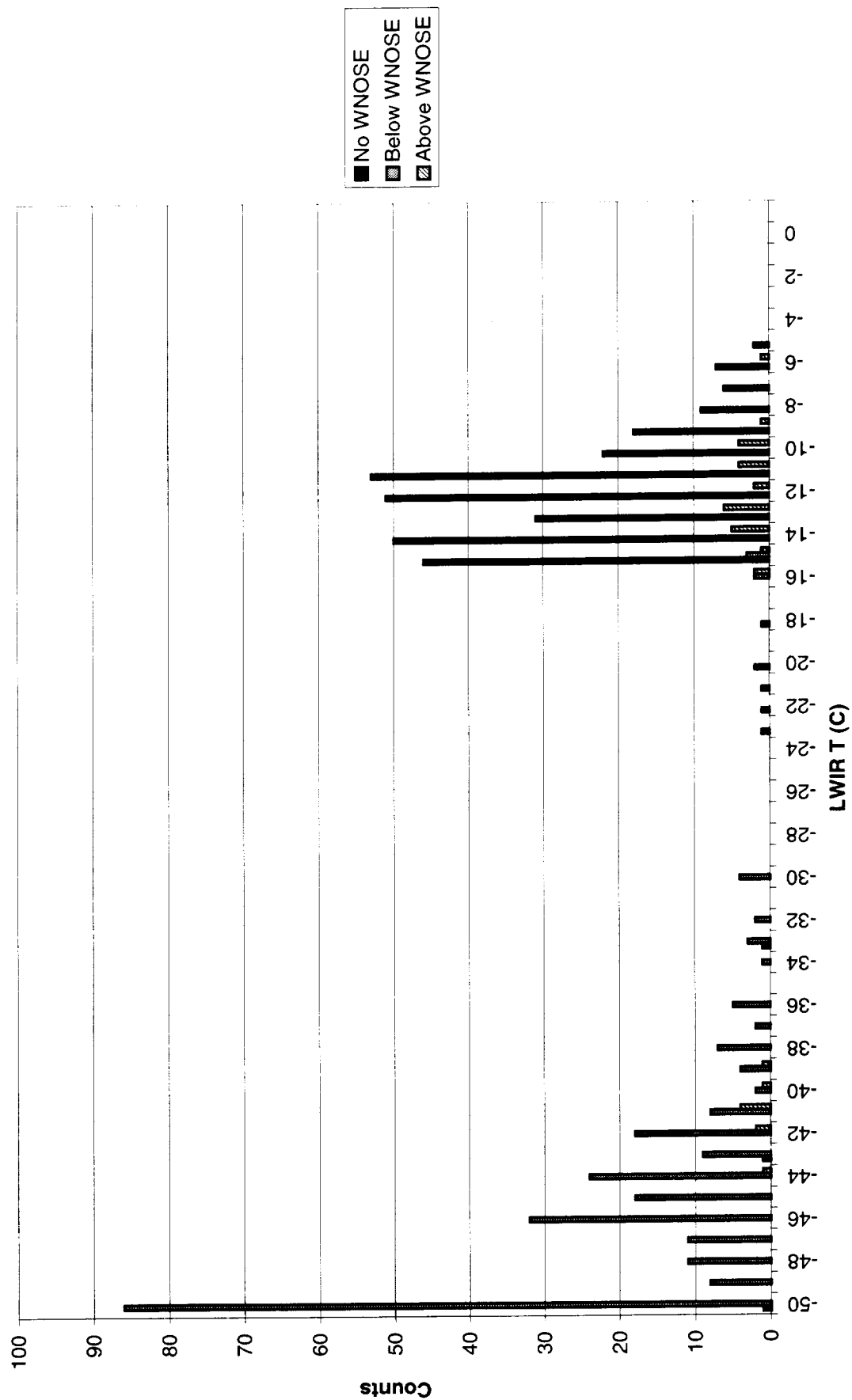
Figure 1b - Mean LWIR Temps for SLD-3
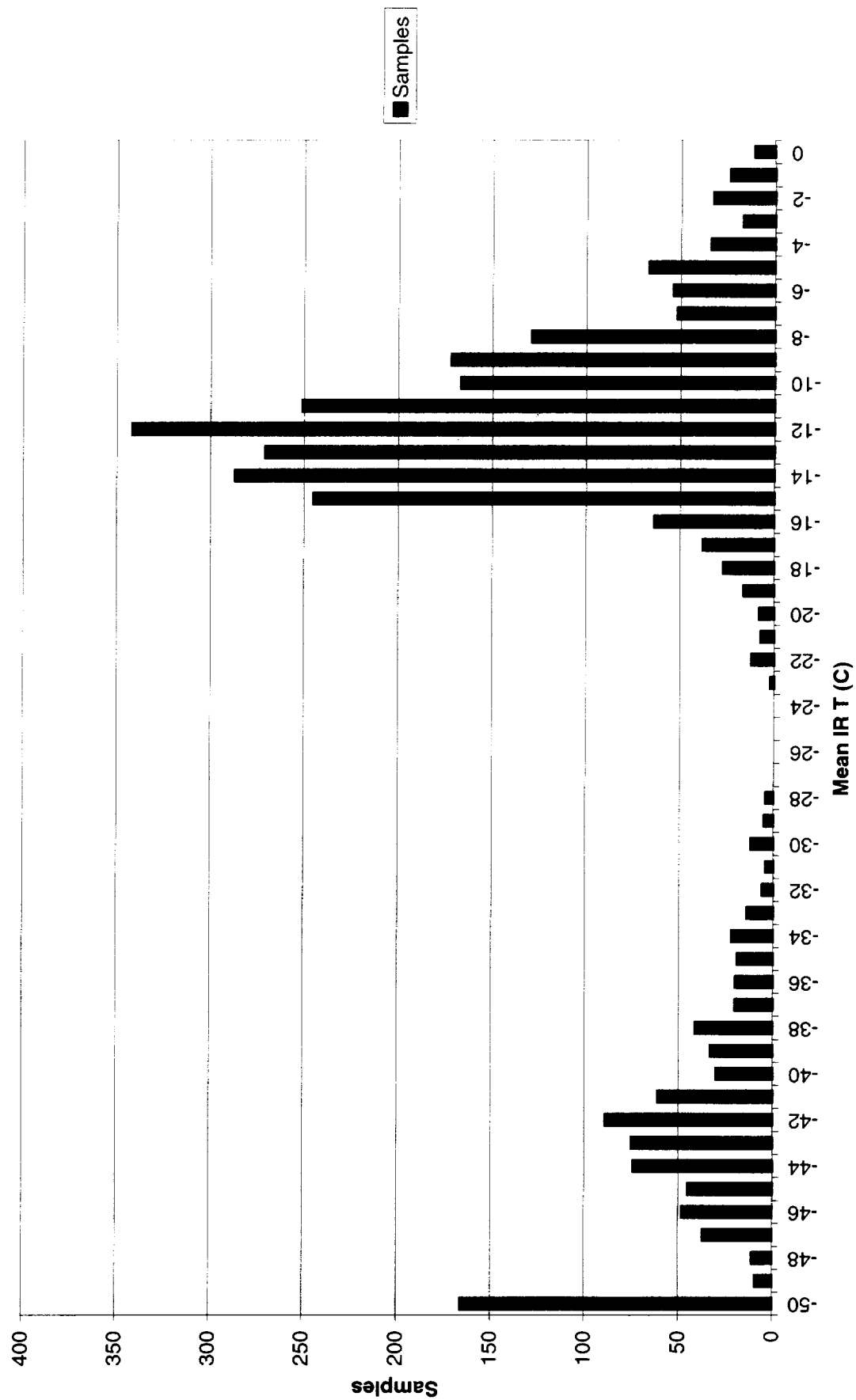
Figure 2 - Mean IR Temps (C) - # of Samples

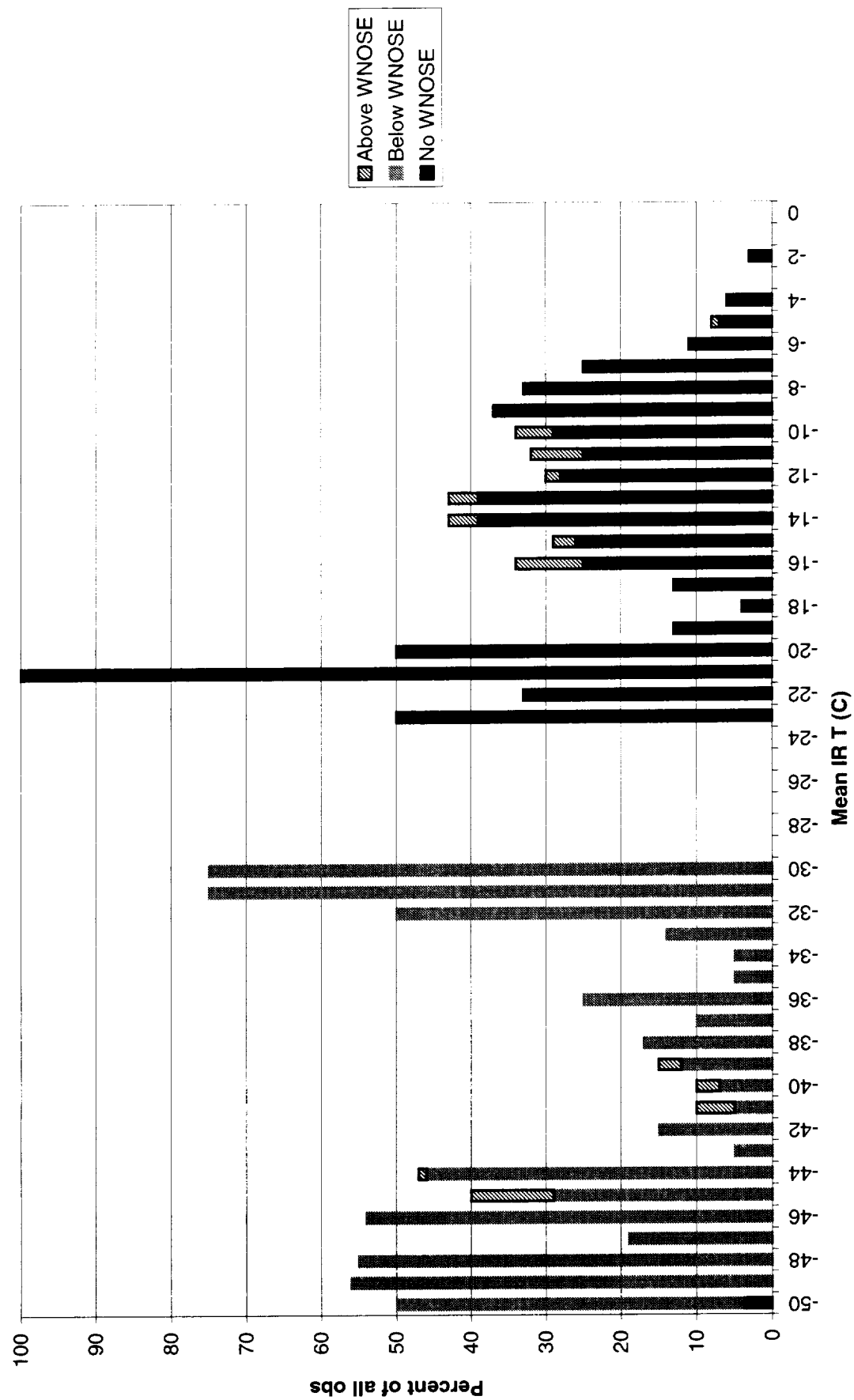Figure 3a - Mean IR Temps (C) for ICE-3, normalized
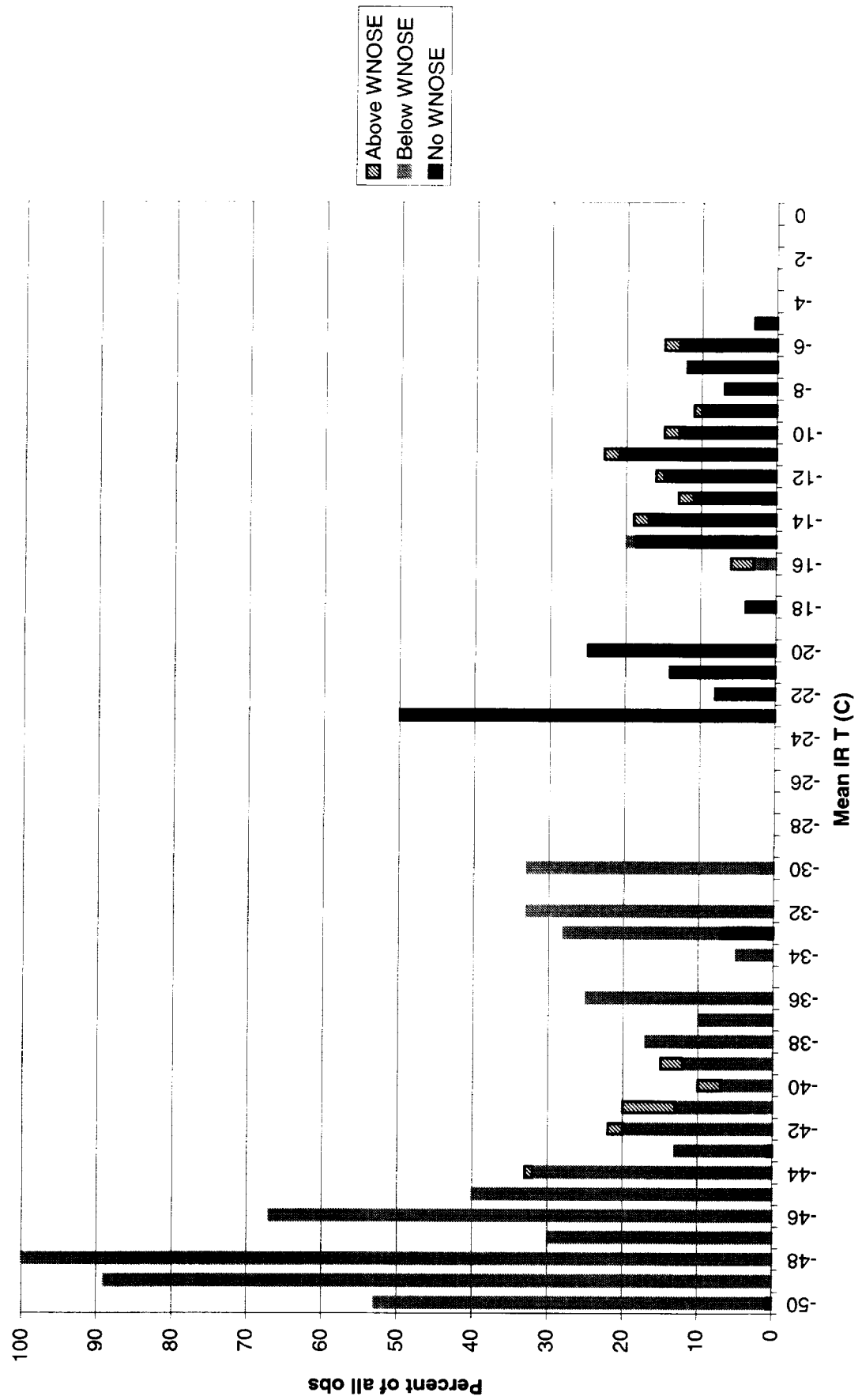
Figure 3b - Mean IR Temps (C) for SLD-3, normalized

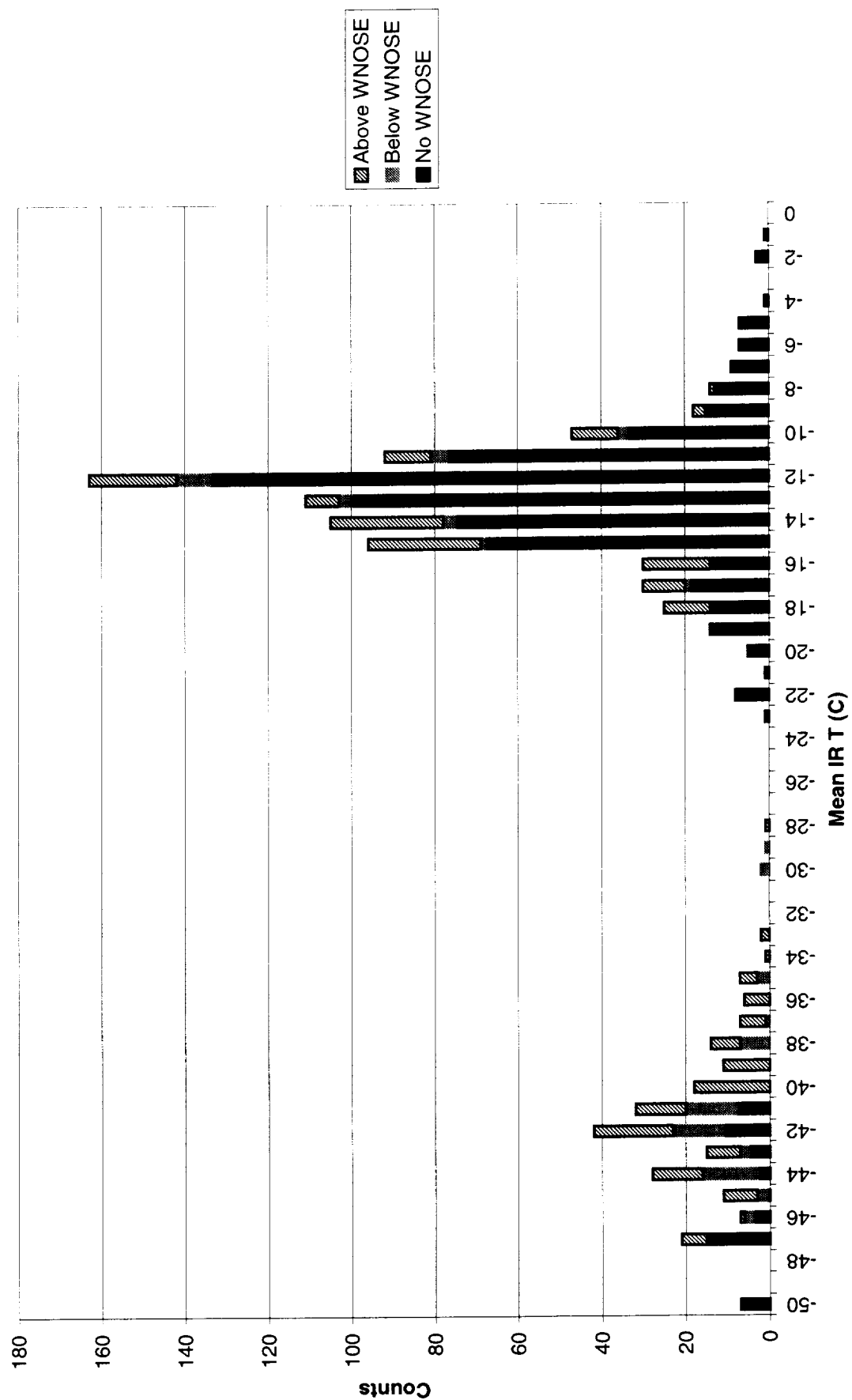Figure 4a - Mean IR Temperatures (C) for Ice Crystals=YES
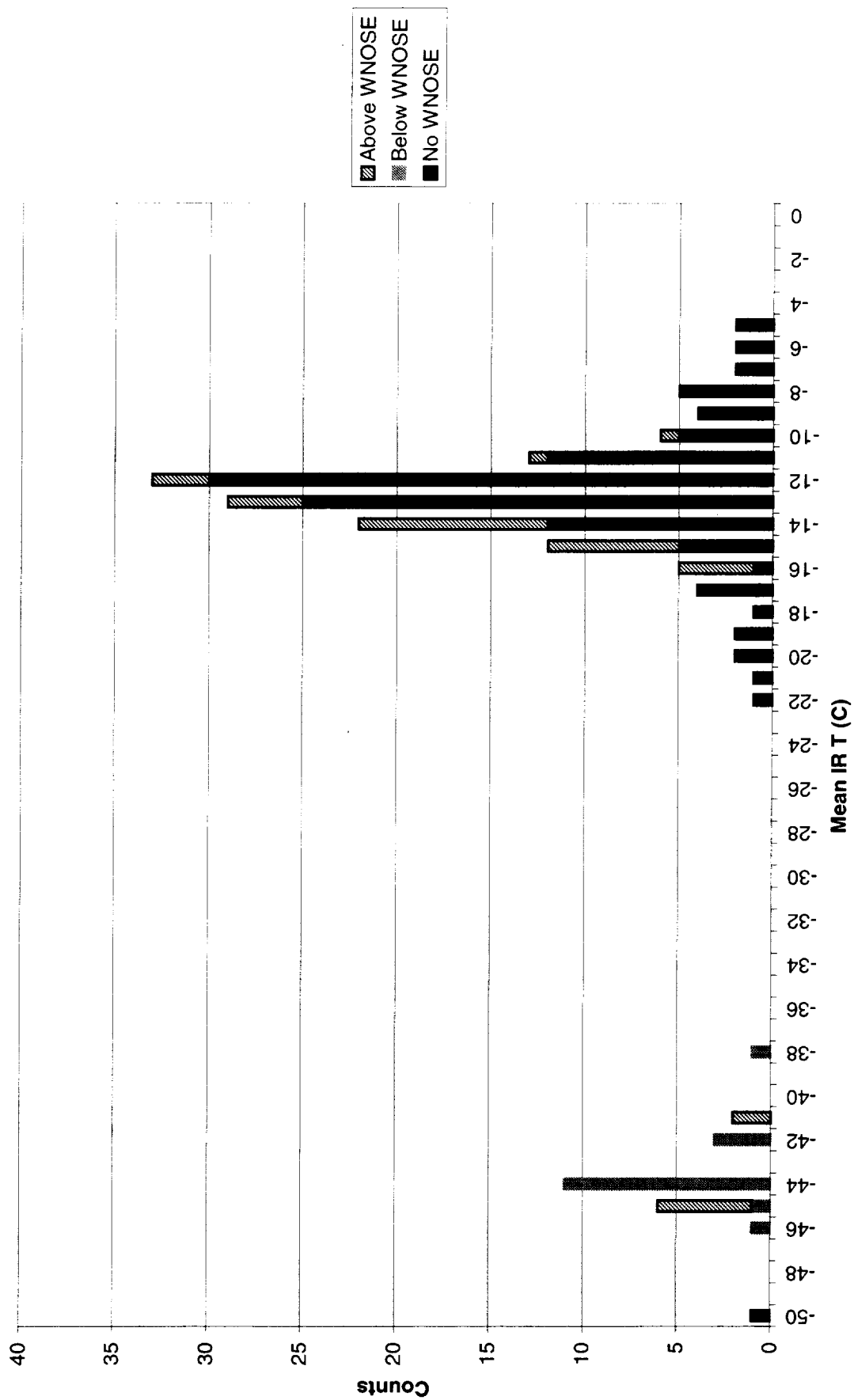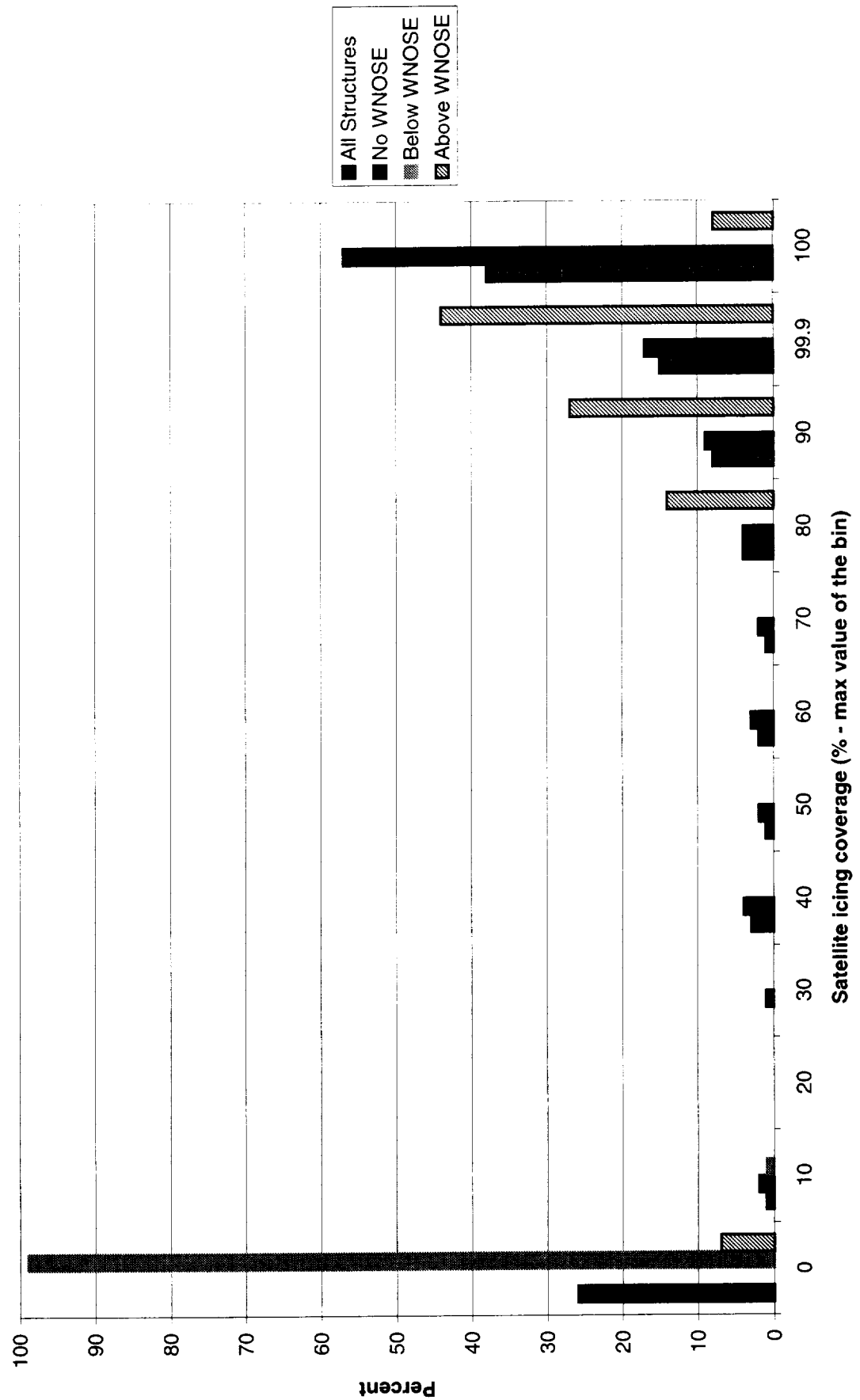
Figure 4b - Mean IR Temps (C) for MIXED PHASE

Figure 5 - % of satellite pixels with icing for ICE-3

REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE August 2001	3. REPORT TYPE AND DATES COVERED Final Contractor Report

4. TITLE AND SUBTITLE

Evaluation of NCAR Icing/SLD Forecasts, Tools and Techniques Used During the 1998 NASA SLD Flight Season

6. AUTHOR(S)

Ben C. Bernstein

5. FUNDING NUMBERS

WU–711–21–23–00
SETAR–0088

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Center for Atmospheric Research
1850 Table Mesa Drive
Boulder, Colorado 80305

8. PERFORMING ORGANIZATION REPORT NUMBER

E–12808

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA CR—2001-210954

11. SUPPLEMENTARY NOTES

Project Manager, Dean Miller, Turbomachinery and Propulsion Systems Division, NASA Glenn Research Center, organization code 5840, 216–433–5349.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category: 03   Distribution: Nonstandard

Available electronically at http://gltrs.grc.nasa.gov/GLTRS

This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Supercooled Large Droplet (SLD) icing conditions were implicated in at least one recent aircraft crash, and have been associated with other aircraft incidents. Inflight encounters with SLD can result in ice accreting on unprotected areas of the wing where it can not be removed. Because this ice can adversely affect flight characteristics of some aircraft, there has been concern about flight safety in these conditions. The FAA held a conference on in-flight icing in 1996 where the state of knowledge concerning SLD was explored. One outcome of these meetings was an identified need to acquire SLD flight research data, particularly in the Great Lakes Region. The flight research data was needed by the FAA to develop a better understanding of the meteorological characteristics associated with SLD and facilitate an assessment of existing aircraft icing certification regulations with respect to SLD. In response to this need, NASA, the Federal Aviation Administration (FAA), and the National Center for Atmospheric Research (NCAR) conducted a cooperative icing flight research program to acquire SLD flight research data. The NASA Glenn Research Center's Twin Otter icing research aircraft was flown throughout the Great Lakes region during the winters of 1996–97 and 1997–98 to acquire SLD icing and meteorological data. The NASA Twin Otter was instrumented to measure cloud microphysical properties (particle size, LWC, temperature, etc.), capture images of wing and tail ice accretion, and then record the resultant effect on aircraft performance due to the ice accretion. A satellite telephone link enabled the researchers onboard the Twin Otter to communicate with NCAR meteorologists, who provided real-time guidance into SLD icing conditions. NCAR meteorologists also provided preflight SLD weather forecasts that were used to plan the research flights, and served as on-board researchers. This document contains an evaluation of the tools and techniques NCAR forecasters used to predict the location of SLD icing conditions during the winter of 1997–1998. The objectives of this report are to: (1) assess the tools used to forecast in-flight icing, (2) assess the success/failure rate of the forecasts, and (3) discuss suggested changes to forecast techniques.

14. SUBJECT TERMS

Ice formation; Aircraft icing

15. NUMBER OF PAGES
46

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500