P6.15 A CASE STUDY OF A GREAT LAKES SUPERCOOLED LARGE DROP ICING CLOUD

Frank McDonough* and Ben C. Bernstein
National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307

1. Introduction

It is well known that exposure to supercooled large drop icing (SLD; subfreezing water drops with diameters > 50 μm) can pose a significant threat to the safety of some aircraft (Sand et al., 1984). Following the 1994 crash of an ATR-72 at Roselawn, Indiana, the NTSB identified SLD as a contributing factor to the accident (NTSB 1996). Due to the fact that little research had been done on SLD icing, a field campaign to better understand this phenomenon was undertaken. During the winter of 1997-1998 the NASA Glenn Twin Otter research aircraft began a program to sample clouds containing SLD icing conditions (Miller et al., 1998), and to document the meteorological conditions and cloud processes that form them.

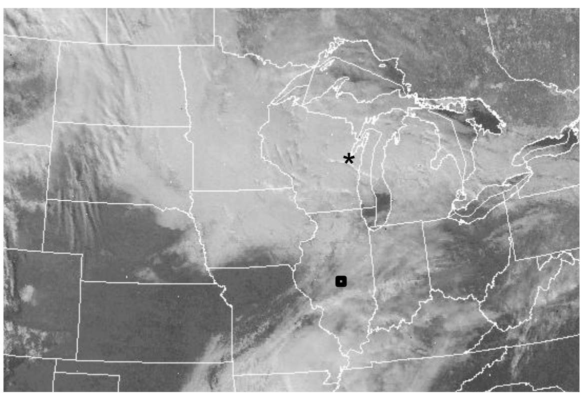

Figure 1. GOES 8 visible image for 2015 UTC on 26 January 1998. KGRB and KILX are marked with a star and a square respectively.

On 26 January 1998, forecasters identified the area near Green Bay, WI (KGRB; Fig. 1) as a good SLD target. The large-scale weather conditions there were similar to those complied for a climatology of freezing drizzle (FZDZ; Bernstein (2000)). Those results indicated that when FZDZ was reported at Green Bay the station would often be north of a stationary or warm front, have a surface high-pressure center over central Ontario and northeast surface flow down the bay. At 2000 UTC (hereafter, times referred to in the format date/hour; e.g. 26/20) the Twin Otter climbed through a multi-layered cloud above KGRB that contained SLD icing. Three distinct layers were present, each with its own microphysical character. This paper will document the synoptic and mesoscale conditions that formed the cloud layers, the evolution of the conditions from 26/12 to the aircraft penetration at 26/20 will be discussed, and the microphysical structure of the cloud layers will be shown.

2. Data

The NASA Glenn Icing Research Aircraft is a modified DeHavilland 6 Twin Otter. The instrumentation on board and used in this study are: a Forward Scattering Spectrometry Probe (FSSP) which measures particles in the size range 2 - 47 μm; a two-dimensional Optical Array Cloud Probe (OAP 2D-C Gray) which measures and records images of particles in the size range 7.5 - 968 μm; a CSIRO Liquid Water Content (LWC) probe; a Rosemount Outside Air Temperature (OAT) probe; and a Rosemount icing detector. Standard National Weather Service data, including soundings, upper air charts, METARs, and pilot reports are also used to describe the case.

3. Synoptic Scale Structure

At 500hPa on 26/12 a high amplitude jet stream pattern was in place, with a building ridge over the northern Rocky Mountains and a deep trough over the Great Plains. A relative vorticity maximum was within the trough over northern Iowa (Fig. 2a). At the top of the ridge axis, over the western Canadian prairie, the flow split and the weaker polar branch flowed southeast across Ontario. A weakening low, cloudy conditions, weak positive vorticity advection, and westerly flow were all present over KGRB. Embedded in the polar stream was a negative vorticity minimum associated with a short wave ridge near the west end of Lake Superior.

The flow at 700hPa was similar to the trough and ridge pattern seen at 500hPa. Positive advection of θ_e, and weak warm air advection (WAA) was occurring in westerly flow at KGRB. The back edge of the θ_e gradient was

* *Corresponding author address:* F. McDonough, NCAR/RAP, P.O. Box 3000, Boulder, CO 80307; e-mail: mcdono@ucar.edu

just to the southwest. Widespread cloud cover was present at this level.

At 850hPa a trough was also evident (Fig 2b). Cold air to the northeast of the trough is associated with a high, that formed beneath the shortwave ridge. Southerly flow and WAA interacting with the cold air has produced a frontogenetic region near KGRB, with a sharp 8^{o}C gradient across WI. Over KGRB saturated conditions were present due to the cross-frontal lift.

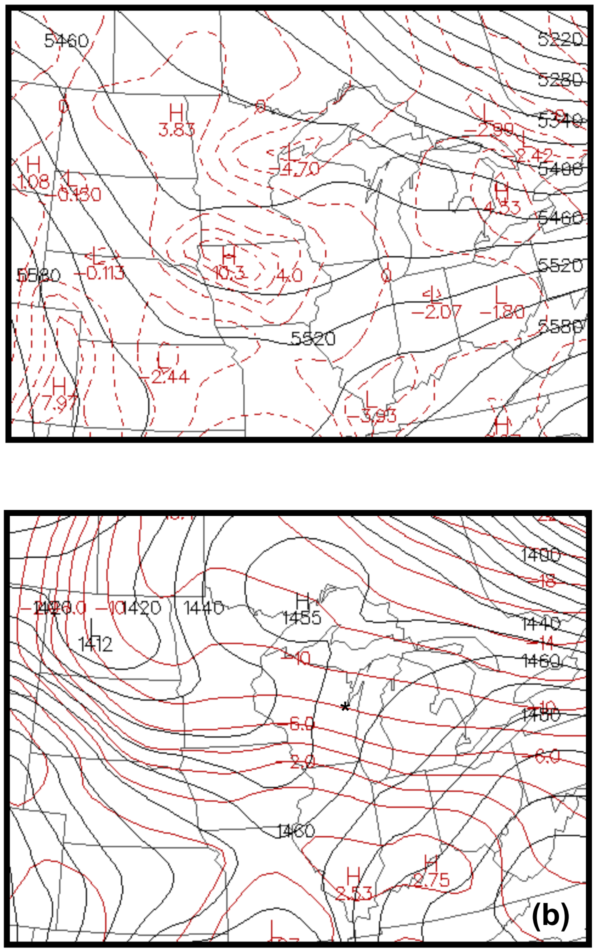

Figure 2. 26 January 1998 1200 UTC a) 500hPa and b) 850hPa charts. Solid black contours indicate geopotential height, red lines are contours of, a) relative vorticity (dashed), b) temperature (solid). KGRB indicated by small black star

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A cold 1034hPa surface high was located just north of Lake Superior, beneath the shortwave ridge (Fig. 3). The frontal boundary, between the cold air mass to the north and warmer air to the south, was stalled south of Green Bay forming a stationary front across southern WI. Along and north of the front, easterly and northeasterly flow dominated and spotty light snow was reported.

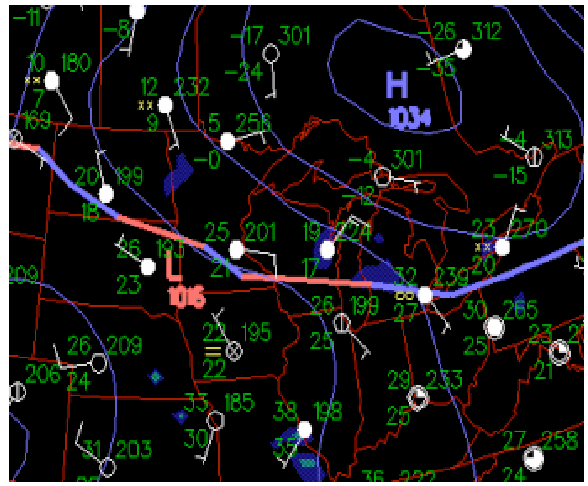

Figure 3. Surface analysis at 26 January 1998 1200 UTC. Echo intensity indicated by blue shading.

4. Mesoscale Features

4.1. Vertical structure at 1200 UTC

The KGRB sounding at 26/12 was launched during intermittent light snow. The temperatures were < 0^{o}C at all levels and a complex vertical structure was present, with four distinct layers (Fig. 4).

Layer 1 was located between 500hPa and 650hPa. It had a weakly veering vertical wind profile indicating warm air advection. The cloud top temperature was –27^{o}C and the layer appeared to be ice saturated.

Layer 2, between 780hPa and 650hPa, had west-southwesterly flow. A 2.5^{o}C inversion isolated this layer from Layer 1. Layer 2 was saturated with temperatures more conducive to supercooled liquid water production than those found in Layer 1, -8^{o}C to -14^{o}C, (Rogers and Yau 1989; Rauber et al., 2000). Ice crystals forming in Layer 1 were likely to have seeded Layer 2, depleting supercooled liquid that could have been produced within it. Cold air advection occurred at its top as indicated by the wind backing with height, whereas WAA occurred at its base.

Layer 3 was present between 960hPa and 780hPa and represents a warm frontal zone (also see Fig. 2b). Winds veered from easterly at the layer base to southwesterly at the top indicating warm air advection. Saturated conditions were present from its base up through the 3°C inversion at its top. Any clouds formed in this layer would have been warmer than –10°C. These temperatures were ideal for the development of supercooled liquid water. However, ice crystals falling from the layers above would have seeded this layer aiding in the depletion of liquid. Some of liquid was present, however, as indicated by a pilot report of light icing at 26/11.

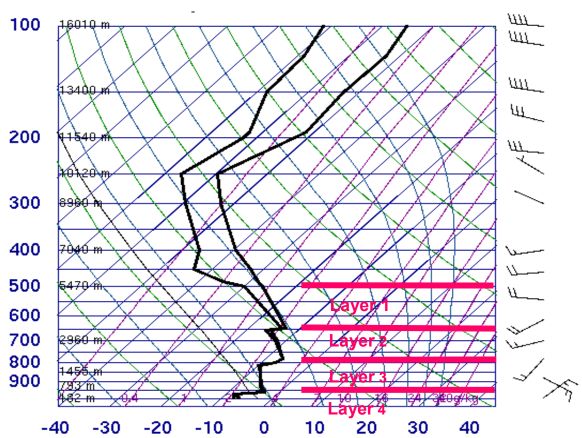

Figure 4. KGRB 26/12 sounding with Layers 1 – 4 indicated.

Layer 4 extended from the surface to 960hPa where there was a 5°C capping inversion. This layer is sub-saturated and much colder than the air above. The clockwise flow around the arctic high (also see Fig. 3) supplied cold air, on a northeasterly flow, across the ice-covered Green Bay.

4.2 Evolution of the cloud layers

A 12-h time series of the vertical structure of θ_e in the lower atmosphere using the 26/12 – 27/00 KGRB soundings and aircraft data will be used to demonstrate the evolution of the cloud layers (Fig. 5).

The clouds in Layer 1 dissipated between 26/12 and 26/20 due to downward motion as weak negative vorticity advection (NVA) replaced the weak PVA that was initially present near 500hPa (also see Fig. 2a). Thus the apparent seeder clouds were eliminated allowing supercooled liquid and freezing drizzle to develop in the layers below. By 26/18 surface observations indicated a change from light snow to freezing drizzle, and icing was reported by a pilot report in the top of Layer 2 at 26/18.

NVA and drier air in Layer 1 also served to lower the cloud top height in Layer 2. Additionally, strong warm air advection below, along with weak CAA at the cloud top tended to destabilize this layer. The inversion between Layers 2 and 3 lowered slightly as the frontal surface moved to the north.

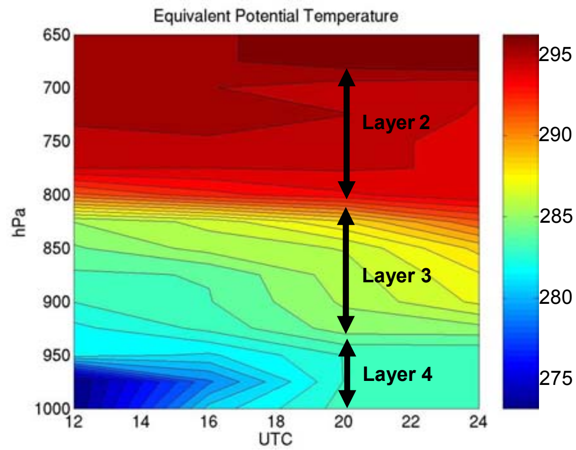

Figure 5. Time series of a vertical cross section of θ_e for the lower atmosphere using the KGRB 26/12, 27/00 soundings and the 26/20 aircraft sounding. Layers 2 – 4 are indicated.

The warm frontal overrunning zone, (Layer 3), continued to feature mechanical lift, as moist southerly flow rode over the colder surface air mass. The frontal slope, as measured between the upper air sites of KILX (see Fig. 1 for location) and KGRB was up to 180hPa, over the 400km between the sites.

The cold dry air initially present within Layer 4 was replaced by a much warmer lake effect cloud that moved westward off Lake Michigan. The arrival of the cloud was accompanied by wind shift from northeasterly to easterly. The cloud top was capped at the 925hPa by the frontal inversion.

5. Structure of the SLD icing cloud

With the synoptic and mesoscale evolution of the cloud described, the thermal and microphysical structure of the SLD cloud can now be demonstrated. The Twin Otter took off at 26/20 and climbed through the multiple cloud layers to reach clear air above 678hPa. The 2D-C Gray imagery and Rosemount icing detector voltage cycles suggested that the clouds were composed almost entirely of supercooled liquid water. Icing conditions were present from just above the surface to the cloud top, except for a cloud free, layer between 744hPa and 704hPa.

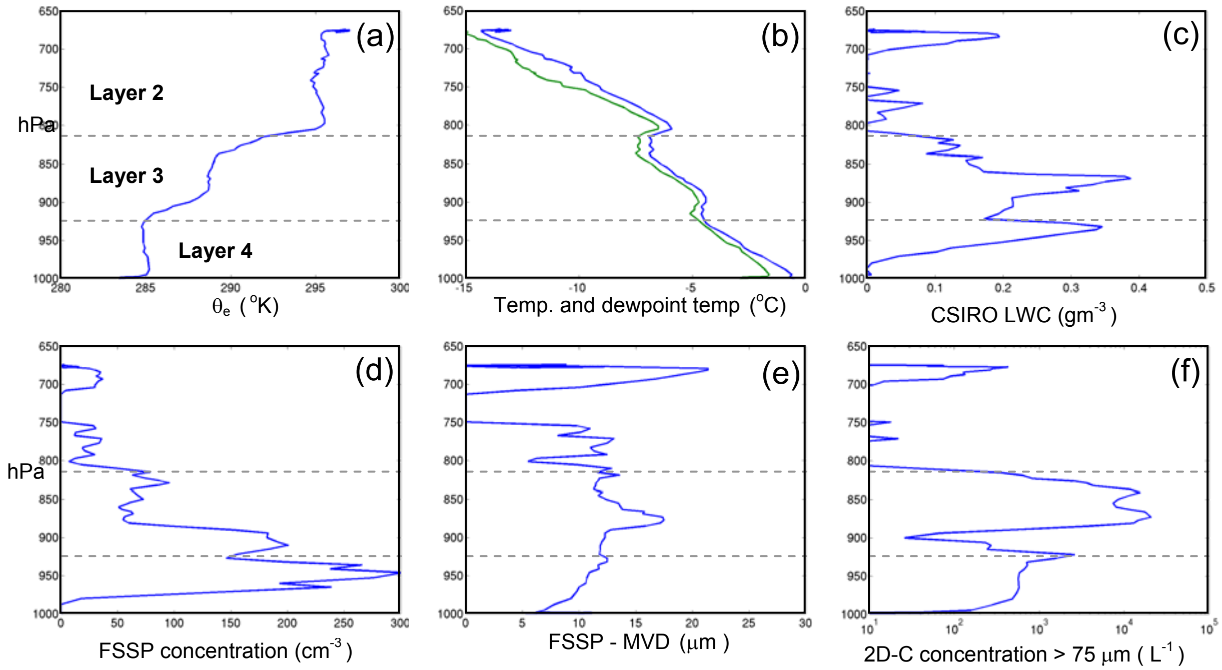

Figure 6. Thermodynamic and microphysical vertical profile of the cloud at KGRB from the Twin Otter. (a) Equivalent Potential Temperature (°K), (b) Temperature and dewpoint temperature (°C), (c) Liquid water content (gm^{-3}), (d) FSSP-concentration (cm^{-3}), (e) FSSP-median volumetric diameter (μm), (f) concentration of particles larger than 75 μm for the 2D-C Gray (L^{-1}).

With Layer 1 having dried out by 26/20, the highest clouds were now found in Layer 2. The warm advection in the middle of this layer formed two distinct shallow cloud layers (Fig. 6). The upper cloud layer (704hPa – 678hPa) had temperatures near -13°C and a liquid water content (LWC) near 0.2 gm^{-3}. Very low FSSP-measured drop concentrations were present and their median volumetric diameter (MVD) exceeded 20 μm while the largest drop diameters reached ~75 μm (small SLD). The lower cloud was more weakly forced, had a low LWC 0.05 gm^{-3} with the similar drop concentrations and only small drops. Both of these layers were generally unstable and separated by the stable cloud free WAA layer.

The icing was significant in the upper portion of Layer 2 with the cold temperatures, LWC of 0.2 gm^{-3}, and small SLD. It was isolated from the boundary layer by several temperature inversions. In addition, precipitation had fallen through this layer removing cloud condensation and ice nuclei (CCN and IN). The lack of IN minimized ice crystal formation and the low CCN numbers produced low drop concentrations which reduced the competition for the condensed water vapor. The result is a relatively cool, thin, SLD icing cloud layer.

The warm frontal layer, Layer 3, was seen between 925hPa and 810hPa. An unstable (constant θ_e) portion of the warm front, between 890hPa and 830hPa, was bounded by large θ_e inversions below and above (Fig. 6). In the lower part of the constant θ_e layer (880hPa) the LWC had increased to 0.4 gm^{-3}. Slight warming, seen in θ_e above 860hPa, appears to limit the LWC production. Drop concentrations were 70 cm^{-3} in the constant θ_e layer.

The constant θ_e layer within the warm front, with its high LWC and fairly low drop numbers had a much larger FSSP-measured MVD than the layers above and below. The lower drop numbers are due to the cloud base location above the boundary layer inversion, and in an air mass with a history of precipitation scavenging reducing CCN and IN. In this relatively clean air mass; drop diameters exceeded 135 μm. Presumably, these SLD fell into the lake effect cloud layer below. Strangely though, the SLD concentrations drop off in the lower inversion, and then increase again in the boundary layer cloud below (Layer 4). Sample volume questions need to be addressed for using the 1997 – 1998 NASA 2D-C Gray data to better asses the meaning of these signals.

The icing conditions in the highest LWC portion of Layer 3 were potentially hazardous. Along with the significant LWC, the temperatures were cold enough for most aircraft to accrete ice, and drop sizes were large enough to cause ice to form on unprotected parts of the airframe.

In the lake effect boundary layer (Layer 4), θ_e was constant and the LWC reached 0.35 gm^{-3}. The drop concentrations were large, approaching 300 cm^{-3} the FSSP-measured MVDs were fairly small throughout its depth. The high drop concentration and small MVDs, along with the lower numbers of small SLD, hint that the warm frontal layer above was seeding this layer with SLD. The SLD appear to have grown upon falling into the water-rich environment of Layer 4, and eventually fell to the surface as FZDZ (drop sizes exceeding 200 μm were observed by the 2D-C Gray). Bernstein et al. (2004) compared the FSSP droplet concentrations to LWC for a large set of icing clouds and identified those that formed SLD. Their results suggest that the SLD was unlikely to initially form within the lake effect cloud layer, due to the LWC:drop concentration ratio

The temperatures in the boundary layer cloud were near -5°C. Most aircraft that encountered this layer's icing conditions will be on take off or landing where they fly relatively slowly. This cloud layer had potentially dangerous icing conditions associated with moderate LWC and SLD.

6. Summary

At the time of the Twin Otter flight over KGRB, three different cloud layers were present, each with its own unique supercooled large drop icing properties. Important clues (NVA, θ_e advection, lake effect potential) were available in the 1200 UTC synoptic data to forecast the SLD icing cloud as much as 8 hours in advance. The change from cloud layers producing snow at 26/12 to layers producing freezing drizzle at 26/20 was tied to the removal of a layer of cold clouds that was seeding the column. The freezing drizzle reported at the surface provided a direct indication that SLD was present aloft. The SLD appeared to form in the cloud layers where the cloud base inflow was detached from the boundary layer and the resulting drop concentrations were relatively low (as in Bernstein et al. 2004). Inversions in the θ_e profile clearly identified the different layers. The highest LWC and significant icing conditions were associated with the constant θ_e layers. Seams of low LWC and minimal icing conditions were present within the inversions between the SLD layers.

Acknowledgements

We would like to thank the crew of the NASA Glen Twin Otter. This research is in response to requirements and funding by the Federal Aviation Administration (FAA). The views expressed are those of the authors and do not necessarily represent the official policy of position of the FAA.

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