8.6 DIAGNOSIS OF SUPERCOOLED LARGE DROP CONDITIONS USING CLOUD WATER CONTENT AND DROP CONCENTRATION

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1. INTRODUCTION

The hazards associated with icing encounters with supercooled large drops (SLD) have been well documented. Both supercooled drizzle and rain aloft can cause ice to form beyond the protected parts of an aircraft. Such ice can have non-conformal shapes and has been shown to result in increased drag, decreased lift and even loss of control (e.g. Sand et al. 1984; Marwitz et al. 1997; Bernstein et al. 1999). Climatologies of surface observations suggest that most SLD develop via the collision-coalescence process (Bernstein 2000; Cortinas et al. 2004). Maritime air masses have been shown to be particularly conducive to this process, presumably because their clean nature is favorable to the formation of clouds with low drop concentrations. Continental air masses typically contain larger concentrations of cloud condensation nuclei (CCN), so there is a tendency toward clouds that are dominated by small drops (Rasmussen et al. 2002). However, non-classical SLD are commonly observed in continental regimes, both at the surface (as freezing drizzle; Bernstein 2000) and aloft (e.g. Cober et al. 2001). For SLD to form in such an environment, it is suggested that either the liquid water content (LWC) must be large enough or the cloud drop concentration must be small enough so that a collision coalescence process can be effective.

As part of several field programs, NCAR meteorologists have directed the NASA Glenn Research Center's Twin Otter research aircraft into a wide variety of icing situations, many of which included SLD. Through this experience, other field programs, case studies and climatological research, patterns that associate SLD formation with characteristic LWC and drop spectra have begun to emerge. The interplay of some synoptic- and meso-scale forcing, and clouds with certain temperatures, moisture contents, and thermodynamic structures appears to be important to the amount of water and the drop size ranges produced. In this paper, Twin Otter observations of icing clouds with different combinations of LWC and drop concentration will be related to surface and upper air patterns, as well as to local thermodynamic structure, to assess the mechanisms associated with SLD and non-SLD icing scenarios.

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2. DATASETS AND CASE SELECTION

2.1 NASA Twin Otter Research Aircraft

The NASA-Glenn Research Center's Twin Otter research aircraft has been used to study icing conditions for decades. From 1997 to 2004, its flight campaigns have focused on SLD and high LWC conditions (e.g. SLD Research Program [Miller et al. 1998], the Alliance Icing Research Study [Isaac et al. 2001]). The Twin Otter carries an array of probes to document state parameters, cloud microphysics and aircraft flight characteristics. For this study, the probes of interest are as follows: CSIRO liquid water content (King et al. 1978; gm^{-3}), Forward Scattering Spectrometer Probe (FSSP; size range 2-47 microns, concentrations in cm^{-3}), and the OAP 2D-Grey probe ("2DG"; size range 7.5-968 microns). All data presented are from 10-second averages. Note that the CSIRO probe responds well to small drops, but underestimates the water content associated with drops larger than ~50 microns (Biter et al. 1987).

At all times during flight, NASA pilots were vigilant about safety, and constantly assessed the performance of the aircraft. Performance effects were often directly measured via flight maneuvers made immediately after icing encounters. In-flight and post-flight comments from the pilots and engineers regarding the severity of the icing and the character of the ice formations were noted, when available. Photographs were often taken to document ice shapes.

2.2 Definition of SLD

For the purposes of this study, SLD is defined as drops that are clearly visible and fully shadowed on the 2DG probe; those with diameters greater than ~100 microns. All SLD cases described here fell within the drizzle size range (100-500 micron diameter) and formed via the collision-coalescence process. The presence or absence of SLD and ice crystals was derived from examination of the 2DG probe imagery and flight notes.

2.3 Case Selection

Icing is encountered in a variety of situations, including mixed-phase clouds, multi-layered clouds, and in cold air beneath melting zones. To get the best insight into the environmental effects on drop size, this study was limited to clouds that were isolated from all other cloud layers (no seeding from aloft; in most cases there were no clouds above) and contained few or no ice crystals. The upper-most portions of the clouds were studied, so that no precipitation from higher parts of a given cloud layer could affect the drop size distribution. In most cases, vertical flight profiles were used in conjunction with forecaster and on-board researcher flight notes to make these determinations.

Twenty-seven cloud layers were examined. Cases were selected when the microphysical observations were assessed to be of reasonably good quality, self-consistent and included vertical profiles. These cases include all icing conditions, not just those where SLD was observed. The clouds were primarily sampled over northern Ohio, Montreal and Ottawa during the cool season (November to March). All clouds sampled were at altitudes between 3,000 and 14,000 ft MSL, and occurred at temperatures warmer than $-15^{o}C$. For safety reasons, all observations were taken during daylight hours, and no data were obtained in areas of deep convection.

3. ICING ENVIRONMENTS

3.1 "Small Drop" and "SLD Likely" Domains

A chart of the FSSP-measured drop concentration and CSIRO-measured LWC for all 27 cases shows the range of conditions sampled (Fig. 1). LWC and concentration values ranged from 0.07 to 1.1 gm^{-3} and 10 to 435 cm^{-3}, respectively, and include cases with and without SLD. As one would expect, the balance between LWC and drop concentration gives a good first cut at the drop sizes observed. Samples dominated by cloud-sized (small) drops tend to occur toward the upper-left, where the ratio of water content to drop concentration is low, while drizzle-sized (large) drops become increasingly common toward the lower-right portion of the chart, where drop concentrations are lower and/or water contents are higher. For example, with drop concentrations of 200-350 cm^{-3}, drizzle only begins to appear once water contents exceed ~0.4-0.5 gm^{-3}, and don't become strongly evident until they exceed ~0.6-0.7 gm^{-3}. When water contents of 0.1-0.4 gm^{-3} were combined with relatively high drop concentrations (>~200 cm^{-3}), the result was a small drop cloud. Drizzle began to appear as the concentrations decreased beyond ~200 cm^{-3}.

The chart can be divided into two general domains. The "small drop" domain resides in the upper-left corner, where the ratio of LWC to drop concentration is low (<~2 x 10^{-9}g), where only cloud-sized drops were typically found. FSSP-measured median volumetric drop diameters (MVDs) were typically near 10 microns in this region. The "large drop" domain is in the lower-right corner, where the ratio is higher (>~2 x 10^{-9}g), and FSSP MVDs usually fell between 15 and 22 microns. This is where SLD in the form of drizzle is often present. Small drops are often mixed with the drizzle and may contribute a large portion of the water content. Note that LWCs in this domain are likely to have been underestimated by the CSIRO probe, due to its reduced response to large drops. It would be valuable to calculate full drop spectrum LWCs, using both the FSSP and 2DG probes, which may result in some markers on Fig. 1 moving to the right. A dashed line on Fig. 1 between the "small drop" and "SLD likely" domains roughly indicates the transition between these regimes. Realistically, there is more of a transition zone that will depend upon the breadth of the drop size distribution.

There were three notable exception cases that fell into the "SLD likely" domain, yet SLD was not observed (no circle around the data points on Fig. 1). Examination of the FSSP data indicated that the drop size spectra were quite narrow in these cases. They were typically centered near 20 microns and had few, if any drops at sizes larger than 40 microns. It seems that the lack of broadening of the distributions kept SLD from forming in these cases, despite the presence of favorable ratios of LWC to drop concentration.

Now that the cases have been roughly categorized, we seek a better understanding of the environments in which different combinations occurred. Vertical profiles of Twin Otter data were examined to determine the vertical stability present above, below and within the cloud layers studied here. Surface and upper-air charts were used to put the cases into a synoptic-scale weather context.

3.2 Stability and Synoptics of clouds with high drop concentrations

Cases with relatively high drop concentrations were generally associated with airmasses rooted in the boundary layer. Vertical temperature profiles typically had dry adiabatic lapse rates below cloud base, moist adiabatic lapse rates within the cloud layer and strong inversions just above cloud top. This "capped convection" scenario often results in widespread stratocumulus clouds with fairly uniform tops. Such situations are common in the wake of

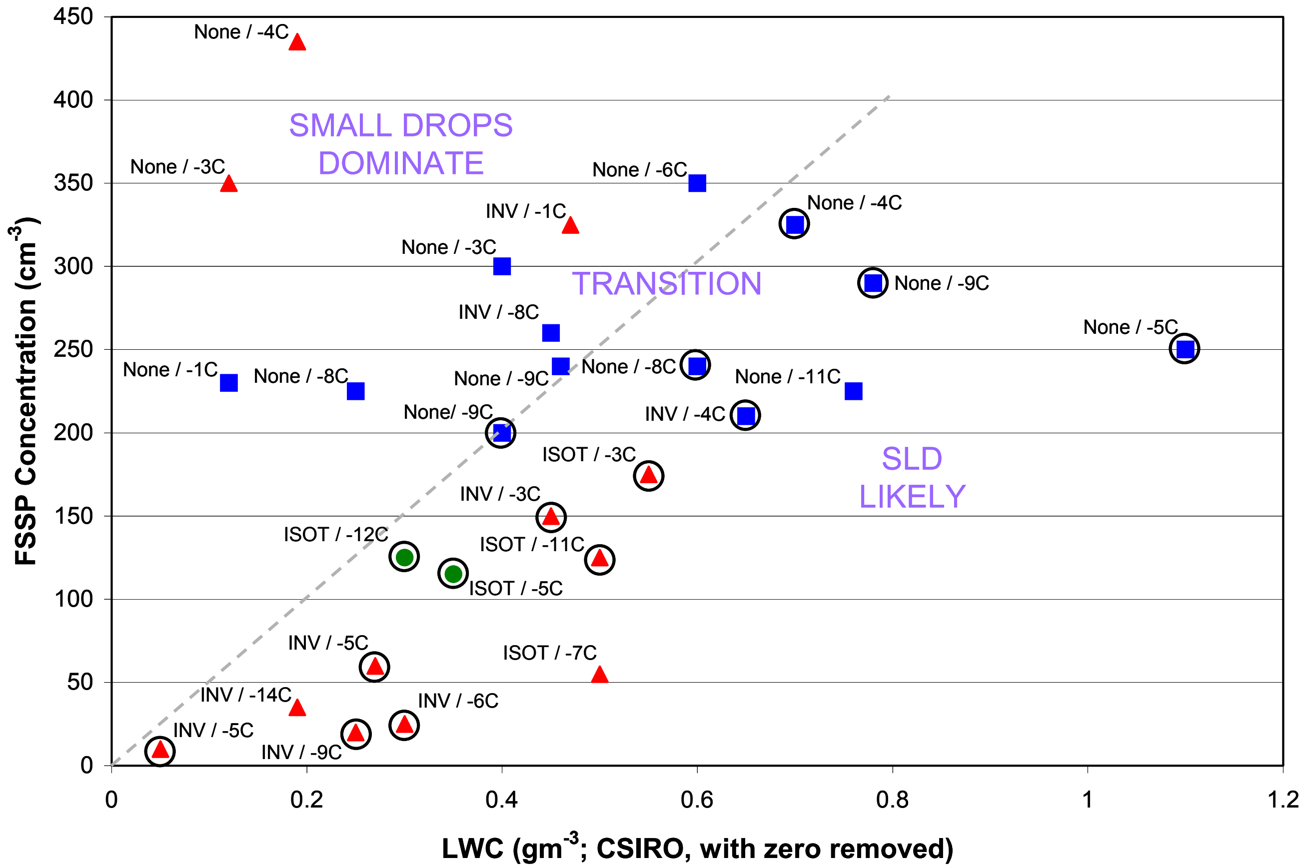


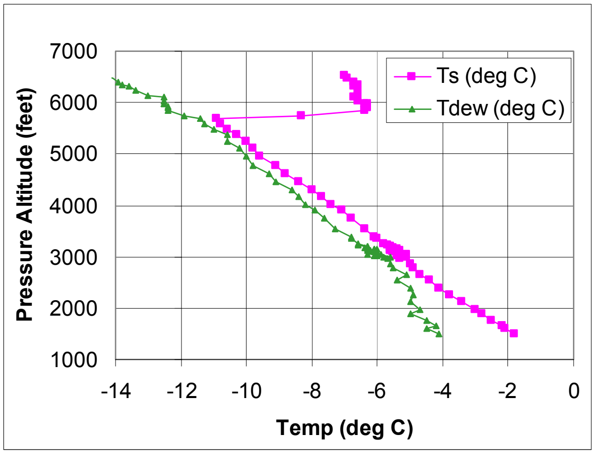
Fig. 1. LWC vs. FSSP-measured drop concentration and temperature advection for the 27 cases. Markers are colored and shaped by the predominant temperature advection present: warm (red triangles), cold (blue squares), neutral (green circles). If SLD was observed, then the marker is circled. The inversion strength beneath the icing layer (INV=inversion, ISOT=isothermal, NONE=no inversion) and the temperature at which the conditions occurred are indicated with text, usually above and to the left of the marker. A grey, dashed line indicates a 2×10^{-9} g ratio of LWC:drop concentration (FSSP).

cold fronts, where strong cold air advection quickly destabilizes the lower atmosphere, but the lack of cold advection above the cold front results in a strong cap. These post cold frontal stratocumulus layers are dominated by cloud-sized drops, unless relatively high water contents are reached.

An example profile of temperature, dew point and LWC from one such case is shown in Fig. 2. The LWC profile has the classic "wedge" look to it, increasing with height to reach 0.75 gm^{-3} and then abruptly decreasing to zero at the cloud top inversion. Drop concentrations were fairly constant (~225 cm^{-3}) with height in this case.

As described earlier, high water contents must be achieved for SLD to form in boundary-layer rooted clouds, and in many cases the SLD tend to be on the small end of the size range. In this situation, the LWC is typically a function of cloud layer depth and cloud base temperature (which determines the saturation mixing ratio), and can be estimated using the adiabatic assumption when the cloud is not precipitating. A key limiting factor for these cases is cloud top temperature. As the cloud layer deepens and higher LWC becomes possible, its cloud top also cools quickly, which may cause the abundant ice nuclei (IN) present in boundary layer air to become active, resulting in partial or total glaciation. Thus, a balance must be struck between cloud layer depth, available water vapor and cloud top temperature.

In boundary-layer rooted clouds, it is somewhat difficult to achieve high enough water content without activating ice processes. This is especially true in cold climates, where cloud base temperatures may already be below freezing, and may explain why such clouds do not commonly produce SLD. In warmer climates, higher cloud base temperatures may



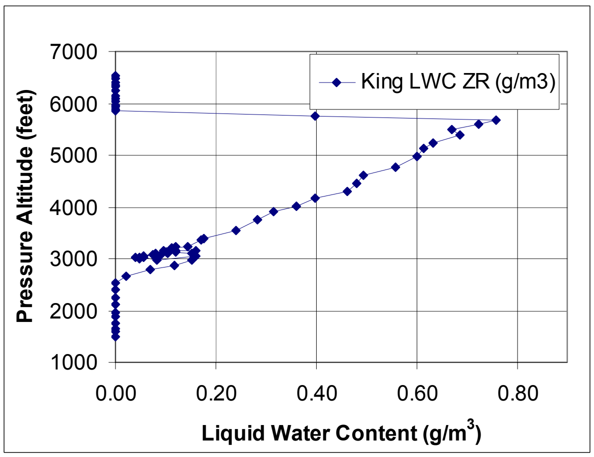


Fig. 2. Vertical profiles of Ts (static temperature), T_{dew} (dew point temperature) and LWC (CSIRO with zero removed) from a missed approach through a boundary-layer rooted cloud on 30 January 1998.

allow for copious amounts of water to reach levels where icing is a threat, and dangerous SLD situations may be the result.

Though many of the boundary-layer rooted clouds occurred in the wake of cold fronts, they were occasionally found within the "warm sector", typically to the southeast or east of low-pressure centers, ahead of cold fronts. Among the 16 cases with relatively high drop concentrations (>200 cm^{-3}), 13 were associated with cold air advection and 3 with warm air advection. Eleven of the cases occurred in the wake of cold fronts, 2 were within the warm sector, 2 were between systems, far from any surface fronts, and 1 was far to the north of a stationary front.

3.3 Stability and Synoptics of "Clean Continental Clouds"

Cases toward the lower portion of Fig. 1 (drop concentrations <~200cm^{-3}) occurred above stable layers and in many cases, strong and/or deep inversions. The stable layers tended to cut off the source of boundary layer air responsible for high drop concentrations. Such situations are commonly found on the cold side (typically north or northeast) of warm fronts and stationary fronts, where warm air gently glides upward over the frontal surface and becomes far removed from boundary layer source air. These overrunning clouds may have lost CCN and IN via precipitation processes, especially near the frontal zone (as in Rasmussen et al. 1995).

Lapse rates within clean continental clouds were highly variable, with some at or near moist adiabatic and others closer to isothermal. There was no clear relationship between LWC and either lapse rate or layer depth. The presence of significant LWC (>0.3 gm^{-3}) with somewhat stable lapse rates is indicative that the upglide associated with warm- or stationary-frontal lift is adequate to form clouds and SLD. Moist adiabatic lapse rates sometimes found in these situations may be associated with local or regional areas of instability above the frontal surface.

Three cases with low drop concentrations that resulted in moderate-or-greater icing severity occurred in areas with breaks in precipitation shields often associated with small areas of warm cloud tops embedded within widespread, relatively cold tops. Such scenarios may support the idea of localized cleansing of the air, helping to form larger drops.

Among the 11 cases with drop concentrations less than 200 cm^{-3}, 9 were associated with warm air advection and 2 with neutral advection. Seven cases occurred on the cold side of warm or stationary fronts, 1 was far to the west of a cutoff surface low, essentially in a wrapped warm front, 2 were in the "warm sector" and 1 was in an occlusion aloft. These results, and those of the previous section, corroborate those found in a climatology of freezing drizzle surface observations by Bernstein et al. (1998).

3.3 Capping Stable Layers – What is Their Role?

It is interesting to note that in *every* case used in this study, the cloud was capped by a stable layer, with many having 3°C or stronger inversions over shallow depths (as in Fig. 2). Many of the cases were dominated by, if not made up entirely of, cloud-sized drops, suggesting that the capped structure, itself, does not appear to be a primary controlling factor in the development of SLD. Rather, when this structure is present, the controlling factors appear to be whether or not the water content can become large enough to overcome the large number of drops that are competing for it, and whether the capping inversion occurs at a sufficiently warm temperature to limit the activation of ice nuclei.

3.4 Downstream Effects – Clouds and Aircraft

Two important issues that are not included in these cases should be discussed. A given SLD layer, itself, may not be particularly threatening to an aircraft because it has a low LWC. However, the layer may have two important potential downstream effects. First, SLD from this layer may grow to sufficiently large sizes to survive the fall through sub-saturated air to reach a cloud layer below. If the lower cloud layer contains significant amounts of supercooled water, then a potentially dangerous combination of water content and drop size may result. Also, the SLD may grow to reach even larger sizes. Such cases have been documented by the Twin Otter (McDonough and Bernstein 2004). Second, any ice that accreted beyond protected surfaces on the aircraft during the initial encounter with SLD may be able to grow to large sizes via the subsequent attachment of small drops, and may result in significant performance degradation.

4. IMPLICATIONS AND CLUES

The results of this study provide insight into the feasibility of SLD diagnosis and forecasting, via assessment of environments prone to certain drop concentrations and their associated water contents. These concepts can be applied manually or automatically via icing algorithms or model microphysics packages.

To assess air mass cleanliness, forecasters can use observed and model forecast soundings to search for stable layers beneath cloud decks in areas where icing is expected. Location relative to frontal features can also provide insight. If the cloud appears to be rooted in the boundary layer (dry adiabatic from cloud base to the surface and moist adiabatic within the cloud layer), is non-precipitating, and the cloud base and top are well resolved, then one can use the adiabatic assumption to estimate the maximum expected LWC (as in Tafferner et al. 2003). Cloud top temperature should be considered, however, to assess the likelihood of ice processes causing partial or total glaciation of the cloud. Surface observations of snow can provide confirmation of this.

If the cloud is being driven by gradual frontal lift (e.g., on the cold side of a warm or stationary front), then the adiabatic assumption is a poor one, and LWC is more difficult to ascertain. Embedded pockets of clouds with moist adiabatic lapse rates are sometimes present, but these are often difficult to detect. In some cases, such conditions were found in gaps in showery precipitation where SLD, rather than glaciated conditions, may be found.

Many current numerical model microphysics schemes use assumed drop concentrations or an LWC threshold to initiate the conversion of cloud drops to rain. A good example of this is the current version of the Thompson et al (2004) scheme in MM5 and its counterpart in the Rapid Update Cycle, which uses 100 cm^{-3} and results in autoconversion starting at ~0.3 gm^{-3}. Figure 1 demonstrates that this combination falls just into the large drop regime, so it is a reasonable choice, and represents a middle ground among airmass types. Of course, drop concentrations can differ depending on the source air, and the difficulty lies in distinguishing between (dirty) continental, clean-continental and maritime air. Thompson et al. (2004) propose the use of geographic location and altitude as a way to choose likely drop concentrations. This is a good first step. Perhaps the use of locations relative to fronts and stable layers could enhance this approach, especially in continental regimes. Additional knowledge about whether or not precipitation processes have affected a given cloud layer may also help.

5. CONCLUSIONS AND FUTURE WORK

This study illustrates the range of combinations of LWC and drop concentration in which SLD and small-drop icing occurs during the Great Lakes cool season, and the synoptic- and meso-scale forcing associated with them. It is clear that there are key features in observational data and model output which can be used to help differentiate between the regimes. Once the regime is identified, one may be able more accurately forecast drop size.

While the results shown here appear to give reasonable insight, more cases need to be studied to fill in gaps on Fig. 1. Mesoscale environments should be studied further to identify fine-scale features that may have played a role in the production of SLD. The potential role of wind shear at cloud top or embedded within the cloud should also be investigated further. Finally, it would be useful to relate pilot assessments of aircraft performance changes and/or icing severity to the water content, drop size and temperatures recorded by the aircraft.

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