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28 000 NMI OF MICROPHYSICAL MEASUREMENTS IN SUPERCOOLED CLOUDS

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1. INTRODUCTION

This large database was originally assembled for improving the understanding of aircraft icing conditions aloft. This paper reports on some of the findings that will be of general interest to the cloud physics community. In particular, the results should be of use to cloud researchers and modelers, icing forecasters, and perhaps climate modelers.

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1.1 The data

Measurements of liquid water content (LWC), drop size, temperature, and other variables were obtained from two generic sources—"old" measurements from the 1940s and 1950s, and modern measurements from the 1970s and 1980s. The old data were from the first extensive set of cloud physics research flights ever undertaken. They were conducted by researchers from the U.S. Weather Bureau and the National Advisory Committee for Aeronautics (NACA) during the winters of 1946 to 1950. Hacker and Dorsch (1951) summarize the results. These flights were dedicated to characterizing icing clouds for the rapidly expanding, postwar, commercial airline industry. They collected ice on rotating multi-diameter cylinders (Jones and Lewis 1949; Ludlam 1951; Brun, et al. 1955) from which they computed average values of supercooled LWC (SLWC) and approximate values of droplet mass-median diameter (MMD) over 1- to 10-minute in-cloud exposures. About 4700 n mi of useful measurements were obtained, primarily over the north central and north western regions of the United States at altitudes up to about 7 km (22 000 ft).

A follow-on NACA project (Perkins 1959) during the early 1950s equipped a number of commercial airliners and weather reconnaissance airplanes with rotating disk icing rate meters. These meters were designed for nearly unattended operation along routine flight routes whenever the airplane encountered icing conditions. Useful data are available primarily from Alaska and the Aleutians, and the North Atlantic, with a smaller number of measurements from Europe and the northwestern Pacific Ocean. All these flights yielded data primarily on SLWC and horizontal extents of icing conditions (from the icing rate meters) and in-cloud temperatures at various altitudes and geographic locations. Drop size information was not available.

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More than 14 000 n mi of measurements from the various NACA flights of the 1940s and 1950s have been obtained from the NACA technical reports and included in the database here, as indicated in Table 1.

For present purposes, "modern" data are measurements obtained after 1973 from flight research projects using forward-scattering spectrometer probes (FSSP) along with hot-wire LWC meters and other complementary sensors.

Existing or archived data were obtained from a number of diverse projects (Jeck 1986). Individual flights were carefully screened for usefulness and data quality. Data from individual probes and sensors were corrected or adjusted, as necessary, according to existing procedures and instructions from the source organization.

The modern data thus incorporated into the database consist of about 5800 n mi of measurements over parts of North America and about 7800 n mi over parts of Europe and South Africa. Table 1 summarizes the data collected according to geographic region and contributing agency.

Analyses presented here show that the NACA data and modern data compare favorably with each other in the determination of LWC and MMD, even though the measuring techniques were radically different.

2. RESULTS

2.1 Supercooled liquid water content

An important question has always been, What are the practical maximum values of SLWC that may be expected to occur, and how do they vary with cloud type, temperature, altitude, and averaging interval? This can be answered in several ways, as described in the following sections.

- STRATIFORM CLOUDS (St, Sc, As, Ac, Ns, Cs, Cc)

Table 2a gives selected cumulative percentiles for SLWC in stratiform clouds. These give the fraction of the 23 000 n mi of measurements in which the SLWC is less than the indicated value. For example, in 50% of the 23 000 n mi, the SLWC does not exceed 0.12 g m^{-3}.

Table 1. Composition of the supercooled cloud database.

Locations	(Data miles)	Contributors	(Data miles)	ID
CONUS	(11 429)	NACA/USAF	(5670)	Z
AK & No. Pacific	(5732)	NACA/USWB	(4713)	C
North Atlantic	(3069)	NACA/Commercial	(3989)	Z
West Germany	(2283)	U. Wyoming	(3682)	Y
Canada	(1837)	MRI/JTD	(3144)	M, J
North Sea	(1386)	DLR	(2283)	D
Sweden	(896)	AES	(1350)	E
Spain	(440)	LAMP	(679)	F
England	(307)	U. Washington	(565)	W
Arctic	(247)	ARC	(486)	H
France	(239)	UMIST	(307)	B
South Africa	(156)	NASA/Lewis	(278)	L
Norway	(46)	U. North Dakota	(272)	N
		NRL	(194)	V
	28 067 n mi	SAWB	(160)	X
		NCAR	(138)	R
		AFGL	(93)	A
		ASI	(35)	O
			28 067 n mi	

Abbreviations:

AES	= Atmospheric Environment Service (Canada) (now Met. Svc. of Canada)
AFGL	= Air Force Geophysics Laboratory (U.S.)
AK	= Alaska
ARC	= Alberta Research Council (Canada)
ASI	= Aero Systems, Inc. (U.S.)
CONUS	= conterminous (or contiguous) United States (lower 48 States)
DLR	= Deutsche Forschungsanstalt für Luft- und Raumfahrt (Germany)
JTD	= JTD Environmental Services, Inc (U.S.)
LAMP	= Laboratoire Associé de Météorologie Physique (France)
MRI	= Meteorological Research, Inc. (U.S.)
NACA	= National Advisory Committee for Aeronautics (U.S.)
NASA	= National Aeronautics and Space Administration (U.S.)
NCAR	= National Center for Atmospheric Research (U.S.)
NRL	= Naval Research Laboratory (U.S.)
SAWB	= South African Weather Bureau
USAF	= United States Air Force (U.S.)
UMIST	= University of Manchester Institute of Science & Technology (U.K.)
USWB	= United States Weather Bureau (U.S.)

TABLE 2a. SLWC in 23 000 n mi of layer clouds.

% of distance that SLWC is less than indicated	SLWC ($g\ m^{-3}$)	Temperature range
50%	0.12	0 to -40 °C
90%	0.35	0 to -20 °C
95%	0.45	0 to -20 °C
99%	0.65	0 to -20 °C
99.9%	1.0	0 to -15 °C

TABLE 2b. SLWC in 5000 n mi of convective clouds.

% of distance that SLWC is less than indicated	SLWC ($g\ m^{-3}$)	Temperature range
50%	0.3	0 to -30 °C
90%	1.0	0 to -20 °C
95%	1.3	0 to -20 °C
99%	2.1	0 to -20 °C
99.9%	3.2	-5 to -15 °C

- CONVECTIVE CLOUDS (Cu, Cg, TCu, Cb)[1]

Selected percentiles for SLWC in convective clouds are given in Table 2b. The largest value of SLWC that has been documented in this database is a brief (0.2 n mi) 5.2 g m^{-3}, but 99.9% of the distance in convective clouds was in SLWCs smaller than 3.2 g m^{-3} and 99% was smaller than 2.1 g m^{-3}.

2.2 Droplet mass-median diameter

For economy of computer memory and simplification of the database, drop-size distributions (available only in the modern data) were not stored as part of the database. Instead, they are represented by the MMD or, in aircraft icing usage, the equivalent median-volume diameter (MVD).

It has been customary in aircraft icing computations to represent cloud droplet populations by the MMD because, for droplets smaller than about 100 µm in diameter, the MMD has been shown to give the same ice accretions as when using the full LWC vs drop-size distributions. Thus, the MMD is a convenient simplification.

Some cloud physicists may prefer the mean diameter as a representative drop size, and this can be obtained from the MMD. For drop-size distributions not extending much beyond 50 µm in diameter, the mean diameter is approximately 55% of the MMD (or MMD ≈ 1.8 times the mean diameter).

Figures 1a and 1b show the observed frequency of occurrence for MMDs in the database. Frequencies are expressed in terms of the number of n mi that has been recorded for each increment in MMD. The solid curve is the cumulative frequency of occurrence according to the right-hand ordinate scale.

It is clear that clouds have a strong preference for MMDs in the 10- to 25-µm range. It is a common observation that MMDs increase gradually in this range with height from cloud base to cloud top. Nevertheless, there is an apparent equilibrium or preferred MMD near 15 µm. Further conclusions are described as follows.

- STRATIFORM CLOUDS

Figure 1a shows that the mode MMD is about 15 µm. About 80% of all MMDs fall in the 10-µm interval from 10 to 20 µm. This means that one could assume that the MMD is within the 10- to 20-µm range with 80% confidence. (About 50% of the MMDs are contained within a narrower 5-µm interval centered at 15 µm.) About 55% of the MMDs are smaller than 15 µm, but only about 10% are smaller than 10 µm. Only about 10% of MMDs are larger than 20 µm, and the few (1.5%) MMDs larger than 30 µm are probably due to occasional occurrences of freezing drizzle. Ninety percent of the MMDs larger than 30 µm were from maritime air masses.

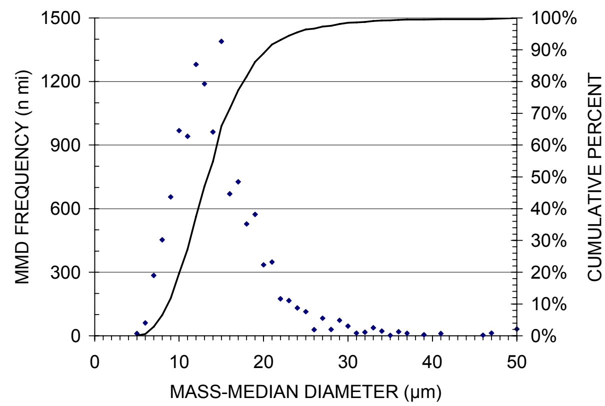

Fig. 1a. MMD frequencies in supercooled stratiform clouds. (12 400 n mi contributing)

- CONVECTIVE CLOUDS

In this case, the MMDs are a little larger. Figure 1b shows that the mode is now about 18 µm. About 80% of all MMDs fall within the 13-µm interval from 12 to 25 µm. This means that in nonprecipitating convective clouds, one could assume that the MMD is within the 12- to 25-µm range with 80% confidence. (About 50% of the MMDs are confined to the narrower 7-µm interval centered at 18 µm.) In convective clouds, about 25% of the MMDs are smaller than 15 µm, but only about 10% are smaller than 12 µm. Only about 10% of MMDs are larger than 25 µm. The few (3%) MMDs larger than 30 µm are probably due to drizzle-sized drops forming in strong updrafts in some of these convective clouds.

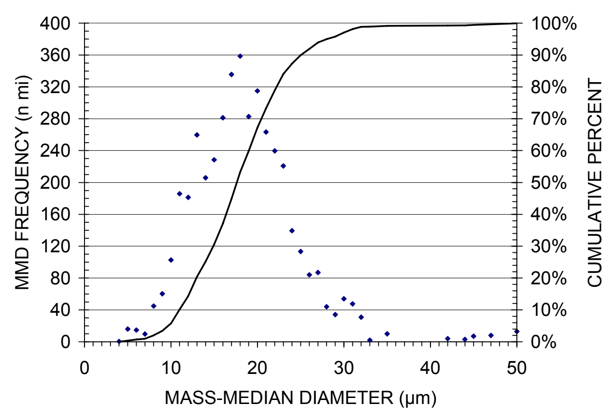

Fig. 1b. MMD frequencies in supercooled convective clouds. (4300 n mi contributing)

[1] Cg = cumulus congestus, TCu = towering cumulus.

2.3 SLWC vs MMD

Another way of looking at MMD probabilities is shown in figure 2. There, the 99th percentile SLWC for various MMDs is displayed as well as the longest distance that a given combination of LWC and MMD can be expected to last. The larger the MMD, the shorter its horizontal extent and the rarer its occurrence. Obviously, MMDs near 15 µm are a preferred or equilibrium state for stratiform clouds, and are where LWCs can be the largest and last the longest.

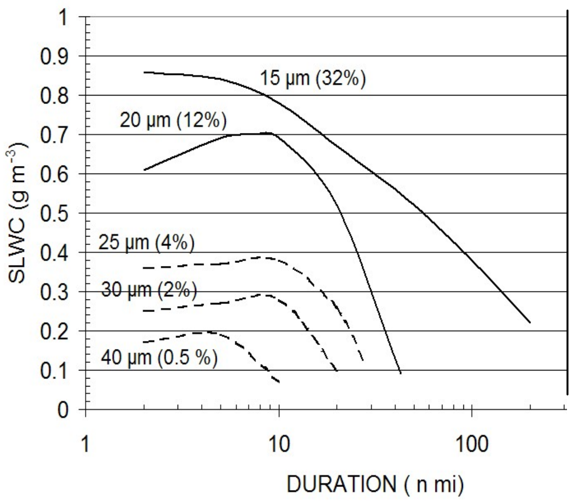

Fig. 2. The 99th percentile limits to SLWC, or duration of same, for MMDs equal or larger than indicated in supercooled stratiform clouds from 0 to -10°C. (Curves will be lower for temperatures below -10°C.) Percentages give the relative frequency of MMDs larger than the indicated MMD. Dashed lines are estimated due to low number of MMDs 25 µm and larger.

2.4 Distance-based graphing.

LWC averages are distance dependent, and average values are generally smaller the longer the averaging distance. In practice, there has been no standard or conventional averaging interval for reporting LWC measurements. Some researchers report instantaneous maximum LWCs observed during a cloud penetration, especially for convective clouds, and some use pass-averages or other arbitrary fixed or variable intervals. Often, the averaging distance is not stated. This makes it difficult to compare LWC measurements from one source to another. The modern data are usually 1-sec samples, and to reduce these to a manageable number for this database, the individual samples have been grouped into *uniform cloud intervals* of variable length (see the Appendix).

The only way to accommodate all these averages of variable length from various sources is to plot the reported LWCs as a function of their averaging distance. The scatterplots in figures 3a - 3c show all 6700 LWC averages contained in the database. It is easy to see that the largest LWCs are confined to the shorter averaging intervals. The plots also show the largest LWCs that have been recorded (in this database) for any given averaging distance.

This is the first time that LWCs have been plotted and compared this way since the early NACA reports (Kline and Walker, 1951). Because the database is now so large, these graphs make a good, *universal* reference standard to which researchers can compare their LWC measurements no matter what the averaging distance.

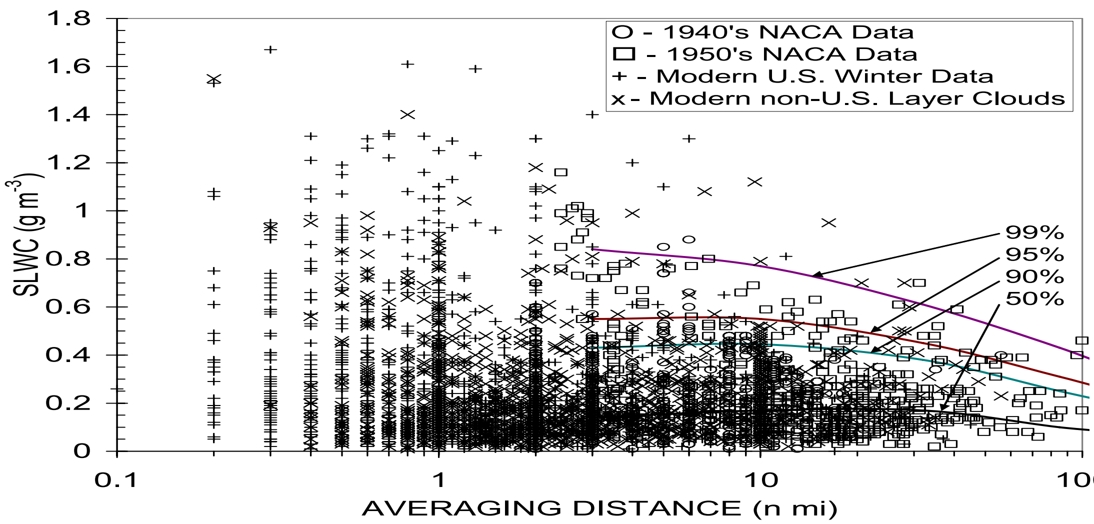

Fig. 3a. 3500 supercooled LWC averages sorted by averaging distance in stratiform clouds. SLWC percentile values are indicated by solid curves. Source of data is indicated by the plotting symbol.

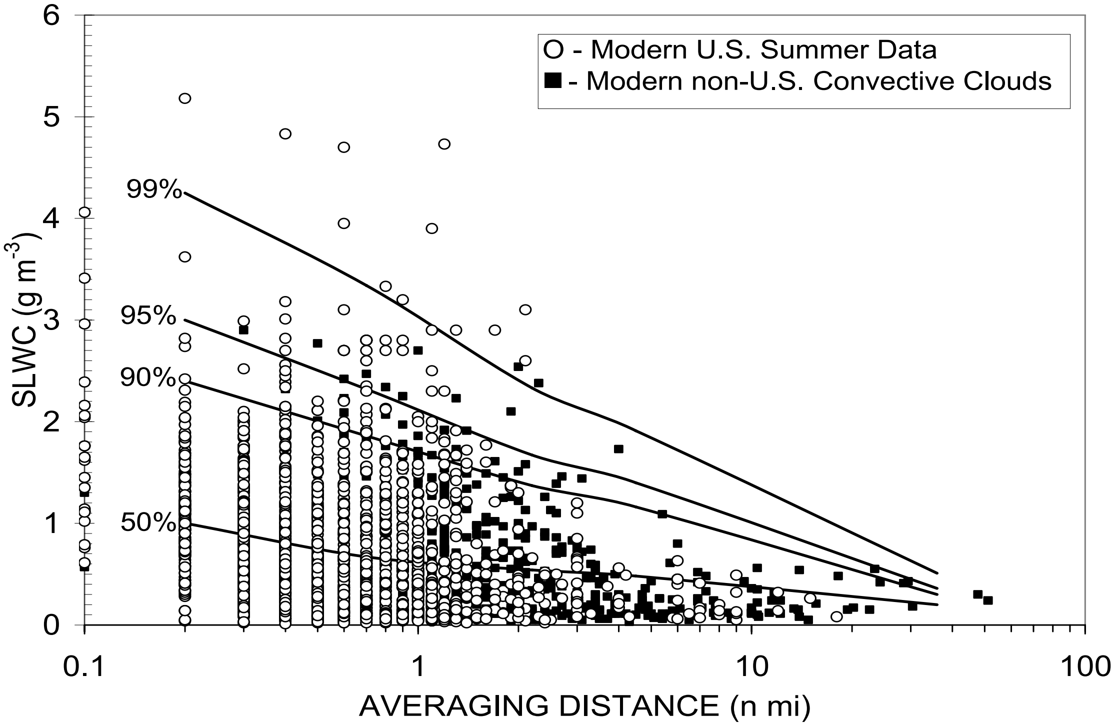

Fig. 3b. 3200 supercooled LWC averages sorted by averaging distance in convective clouds. SLWC percentile values are indicated by solid curves. Source of data is indicated by the plotting symbol.

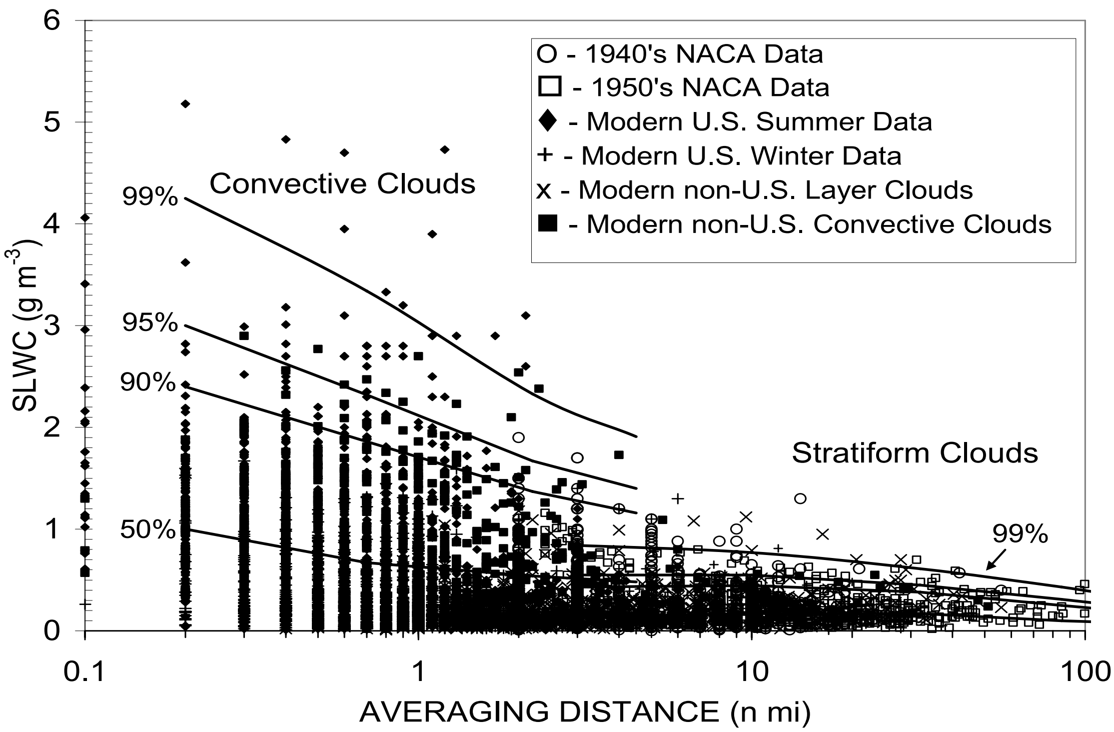

Fig. 3c. The entire supercooled cloud database—6700 averages totaling 28 000 n mi. (SLWCs greater than 1.6 g m^{-3} are from convective clouds.)

3. SUMMARY

This report has presented some new statistics on supercooled clouds, based on 28 000 n mi of in-cloud measurements.

Clouds are shown to strongly prefer droplet MMDs near 15 μm, and it is only for these MMDs that the LWC can be the largest. Smaller or larger MMDs are rarer and persist for shorter periods of time or distance in cloud.

Several innovations for preparing and presenting the data have been introduced and are recommended for general use by the cloud physics community:

- *Uniform cloud intervals* (averages over variable distances where the droplet concentration, MMD, altitude, etc., stay within defined limits) provide an economical way to organize large numbers of 1-sec samples into a manageable set of averages. These preserve essential features of the cloud without sacrificing horizontal or vertical resolution where it is needed. They can also be combined to give longer averages, such as pass-averages, where desired.

- *Averaging distance or duration as a variable weighting factor* is used for frequency-of-occurrence tabulations so that short and long averages are not counted the same.

- *Distance-based graphing* solves the dual problem of (1) comparing values of a given variable (e.g., LWC) averaged over different distances from different sources and (2) depicting limiting values of LWC and MMD as a function of averaging distance.

Originally compiled for characterizing aircraft icing conditions, this largest-ever combined dataset of cloud microphysical variables should also be useful for cloud modeling and parameterization—by providing realistic LWC percentiles naturally scaled to a wide range of in-cloud averaging distances.

Figures 3a – 3c, graphs of SLWC percentiles as a function of averaging distance in stratiform and convective clouds, can serve as a reference standard for cloud researchers who wish to compare their LWC measurements to probabilities based on this large dataset.

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4. REFERENCES

Note: most of the NACA references are available in portable document format (pdf) at
http://naca.larc.nasa.gov/reports/

Brun, R.J., W. Lewis, P.J. Perkins, and J.S. Serafini, 1955: Impingement of cloud droplets on a cylinder and procedure for measuring liquid water content and droplet sizes in supercooled clouds by rotating multicylinder method. NACA Report 1215.

Hacker, P.T., and R.G. Dorsch, 1951: A summary of meteorological conditions associated with aircraft icing and a proposed method of selecting design criterions for ice-protection equipment. NACA Tech. Note 2569.

Jeck, R.K., 1986: Airborne cloud-physics projects from 1974 through 1984. *Bull. Amer. Meteor. Soc.*, **67**, 1473-1477.

Jones, A.R., and W. Lewis, 1949: A review of instruments developed for the measurement of the meteorological factors conducive to aircraft icing. NACA Research Memo. A9C09.

Kline, D.B., and J.A. Walker, 1951: Meteorological analysis of icing conditions encountered in low-altitude stratiform clouds, NACA Tech. Note 2306.

Ludlam, F.H., 1951: The heat economy of a rimed cylinder. *Quart. J. Roy. Meteor. Soc*., **77**, 663-666.

Perkins, P.J., 1959: Summary of statistical icing cloud data measured over United States and North Atlantic, Pacific, and Arctic Oceans during routine aircraft operations. NASA Memo. 1-19-59E.

APPENDIX

DATA MANAGEMENT PHILOSOPHY

The data originally obtained from various sources (digital tapes and tabular reports) have been computerized in a condensed, standardized format according to the following scheme.

1. Basic averaging intervals

Modern, electronic, and electro-optical cloud physics probes and sensors provide digitized measurements typically once per second or more during flight in clouds. A data file may therefore contain 3600 or more individual readouts from each sensor per hour of flight. Naturally, these large numbers of samples have to be reduced in some way to obtain a manageable set of data. The data that are available from technical reports or journal articles have already been condensed to averages over some arbitrary time or distance intervals. For the high-resolution data available directly from digital sources, the following averaging scheme has been devised.

Each variable (LWC, air temperature, droplet number density, etc.) is averaged over continuous, uniform portions of clouds as defined in Table A1. These are termed *uniform cloud intervals* and each constitutes an individual data record. If the aircraft is still in continuous clouds at the end of one uniform interval, then a new averaging interval is immediately begun and continued until the next significant change in cloud properties occurs. Otherwise, the next averaging interval is not begun until the aircraft enters another continuous, uniform section of cloud. This scheme results in variable averaging distances overall, and the averaging distance is retained as one of 75 variables in each data record.

TABLE A1. Rules for defining uniform cloud intervals.

All the measured variables are averaged over the flight path in the cloud until one or more of the following events occurs:
A - Aircraft exits main cloud
B - Outside air temperature changes by ±1.5°C
C - Outside air temperature rises above 0°C
D - Droplet MMD changes by ±2.5 μm
E - Aircraft changes altitude by ±150 meters (±500 feet)
F - Icing rate changes by ±50%
G - Droplet number density changes by ±50% or ±200 cm^{-3}, whichever is less
H - Averaging interval arbitrarily terminated
J - Aircraft encounters momentary break in cloud
K - Subsequent data from ASSP or FSSP is invalidated by snow or ice particles in the cloud

Although these rules were designed for the modern data, pretabulated data from reports or other publications can be formally accommodated as well. The reported averaging distance is used in that case.

This averaging scheme has a number of advantages:

- It avoids inflexible, fixed intervals such as 1-minute averages or averages over entire cloud passes. (These are undesirable if they wash out useful detail otherwise available with modern, high-resolution measurements.)
- The intervals can be short enough to resolve any significant changes in cloud characteristics along the flight path—i.e., the natural variability in clouds can be preserved and documented.
- Intervals of uniform, constant conditions within clouds can be preserved whole so their durations and characteristics can be documented without the ambiguity that would occur if the average included voids or adjacent parcels having significantly different or variable properties.
- The averages can resolve extremes of LWC or other variables without dilution.
- The averages can preserve altitude-dependent changes in cloud properties observed during ascents or descents through clouds.
- The scheme can accommodate broken or scattered cloud conditions as well as widespread continuous clouds.
- Not only are data available on the extents of individual, uniform cloud intervals, but the overall horizontal extent of continuous or semi-continuous cloud conditions is available simply by summing the extents of consecutive uniform intervals.

2. "Data miles" as a measure of frequency of occurrence

During the early phases of this project, it became clear that it was unsatisfactory to define frequencies of occurrence simply as the number of records having a particular value of a given variable. The deficiency was twofold. Firstly, momentary cloud intervals would incorrectly carry just as much statistical weight as long averages. Thus, there was no way to emphasize the statistical importance of an extended encounter with an extreme value of LWC, for example, compared to a relatively insignificant, brief encounter. Secondly, the reader would have no information as to whether a given number of records represented 5 miles or 500 miles of in-flight measurements.

Data miles were, therefore, chosen as the most informative measure of frequency of occurrence. It is simply the averaging distance (in nautical miles), or sum of averaging distances, for any subset of the data. This convention automatically weights each record (or LWC measurement, for example) by its duration or averaging distance. The other principal advantage is that the reader can easily gauge the relative significance of a dataset, subset, or sample by the number of data miles it represents.