CORRESPONDENCE

Comments on "Physical Interpretation of Results from the HIPLEX-1 Experiment"

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ABSTRACT

The aircraft measurements from the HIPLEX-1 weather modification experiment have been examined to determine if the nature of the change of liquid water content (LWC) in the supercooled portion of the clouds can be simply described. Three different data sets were created from the -8 and $-5°C$ aircraft data base. Neither a simple linear nor a simple polynomial fit to the data are suitable for reasons discussed in the text. Two different forms of an exponential model were fit to two of the data sets. When a model for the decay of the maximum 1-km liquid water content (χ) of the form $\chi = \chi_0 e^{bt}$ was fit to data set number two, this yielded a cloud liquid water decay constant (τ) of 560 s (9.5 min), with a correlation coefficient $r = 0.47$ and $r^2 = 0.22$. This reduces the mean first pass χ value of 1.05 g m^{-3} to e^{-1} or 0.39 g m^{-3} in 9.5 min and to $(2e)^{-1}$ or 0.14 g m^{-3} in 19 min. The best fit to the observations, however, comes from a calculation of an average rate of change of LWC at a constant altitude ($-8°C$) in the clouds. This is of the form $\chi = \chi_0 + bt$ and gives a lifetime of 15 min for the maximum 1-km average LWC in the 20 HIPLEX-1 clouds. That is, the highest LWC regions in the upper part of the clouds would be expected to completely disappear in about 15 min. Regions of lower LWC would disappear more quickly. This is a major limitation on both natural and artificial rain forming processes.

1. Introduction

HIPLEX-1 was a very innovative and important weather modification experiment that provided an excellent data set. Smith *et al.* (1984) have described the experimental design and response variables, Mielke *et al.* (1984) the statistical evaluation and Cooper and Lawson (1984) the physical interpretation of the experimental results. Mielke *et al.* found a lack of significant differences in the response variables in seeded and unseeded clouds later than 5 min after seeding. They speculate that one reason for this observation was that suitable conditions for the growth of ice particles initiated by seeding did not exist after this point in time. Evidence for the existence of short cloud top lifetimes in the HIPLEX project area was presented by Schemenauer and Isaac (1980), Schemenauer *et al.* (1981), Lawson (1981), Schemenauer and Isaac (1984) and Cooper and Lawson (1984).

Cooper and Lawson (1984) have calculated a time constant for the decay of the maximum 1-km average LWC (χ) in HIPLEX-1 clouds based on an exponential fit of the form $\chi/\chi_0 = e^{bt}$ to the data. The value of χ on the first aircraft penetration is χ_0. This calculation is repeated below and the applicability and limitation of the resulting time constant is discussed. Time constants from several different fits to the data are compared and the effects on the resulting cloud lifetime calculations evaluated.

2. The HIPLEX-1 aircraft measurements

A total of 20 HIPLEX-1 clouds were studied over the summer months of 1979 and 1980. The supercooled region of each cloud was penetrated by the primary research aircraft for periods of up to 17 min. In Cooper and Lawson's (hereafter CL) Fig. 13, the change with time of the maximum 1-km-average LWC is shown for each cloud. In their Fig. 14, the ratio of the maximum 1-km average LWC to that measured on the first pass is shown as a function of time after the first pass. It is this second figure that provides their evidence for the existence of an exponential decay of cloud liquid water content with time. The actual values used in the production of these figures are not tabulated. There is an apparent problem with Fig. 14. The abscissa is labeled as time after the first pass but in fact the points are plotted at times representing time after seeding. All points in the figure should be moved to the right ≈160 s. Whether this has affected CL's decay constant calculation is uncertain. Tables 1a, b herein present the original measurements as abstracted from Cooper *et al.* (1982a,b). These tables are used to create several different data sets which are discussed in Section 3.

Another matter that is not explicitly mentioned by CL is that the HIPLEX-1 measurements were made at several different altitudes in each cloud and thus their calculation has a built in bias due to variations in LWC with height. Smith *et al.* (1984) explain the nominal procedure that was followed: the pretreatment pass was made at about $-8°C$; the seeding was done by a second aircraft at about $-10°C$; the first two post-treatment passes were targeted for 0.3 km below treatment altitude, or usually around $-8°C$, at about 2 and 5 min after treatment; subsequent passes at about 8, 11, 14 and 17 min after treatment were targeted for the $-5°C$

TABLE 1a. Data abstracted from Cooper *et al.* (1982a,b) for the nominal −8°C level. The *t* values in the table are the elapsed times from the first (pretreatment) aircraft pass. Also tabulated are the maximum 1-km average LWC (χ) for each penetration (e.g., χ_2 is 2 min after seeding) and the ratio of this LWC to that on the pretreatment pass (χ_0). Test cases 1–12 are from 1979, 13–20 from 1980.

	Penetration 1			Penetration 2			Penetration 3		
Test case	*t* (s)	χ_0 (g m^{-3})	$\frac{\chi_0}{\chi_0}$	*t* (s)	χ_2 (g m^{-3})	$\frac{\chi_2}{\chi_0}$	*t* (s)	χ_5 (g m^{-3})	$\frac{\chi_5}{\chi_0}$
1	0	0.79	1	271	0.60	0.76	456	0.50	0.63
2	0	1.79	1	262	0.59	0.33	442	0.19	0.11
3	0	1.09	1	243	0.00	0.00	420	0.00	0.00
4	0	0.52	1	267	0.03	0.06	452	0.03	0.06
5	0	0.98	1	262	0.53	0.54	446	0.61	0.62
6	0	0.68	1	282	0.36	0.53	481	0.29	0.43
7	0	2.51	1	275	1.47	0.59	468	0.12	0.05
8	0	0.93	1	301	0.11	0.12	413	0.30	0.32
9	0	1.02	1	299	0.69	0.68	487	0.35	0.34
10	0	1.71	1	272	0.59	0.35	449	0.07	0.04
11	0	0.89	1	269	0.81	0.91	459	0.61	0.69
12	0	0.56	1	275	0.76	1.36	464	0.67	1.20
13	0	0.75	1	300	0.21	0.28	484	0.02	0.03
14	0	0.56	1	305	0.46	0.82	491	0.44	0.79
15	0	0.81	1	255	0.49	0.60	440	0.31	0.38
16	0	1.13	1	263	0.16	0.14	445	0.00	0.00
17	0	1.09	1	315	0.68	0.62	503	0.26	0.24
18	0	0.59	1	315	0.40	0.68	484	0.88	1.49
19	0	1.67	1	293	0.77	0.46	473	0.45	0.27
20	0	0.97	1	293	0.88	0.91	467	0.67	0.69

level. Thus, in the 17 min covered by CL's Fig. 14 the aircraft has descended perhaps 500 m. Actual penetration temperatures may differ somewhat from these values but the procedure was to be inviolate. Since the LWC increases with height above cloud base (Pruppacher and Klett, 1978) to a maximum somewhere in the upper part of the cloud, one might expect significant changes to appear in the maximum 1-km average LWC purely as a result of the height change. In fact, in a procedure where the change in LWC due to the height change is of the same order of magnitude as the change attributed to the time evolution of the

TABLE 1b. Data abstracted from Cooper *et al.* (1982a,b) for the nominal −5°C level. If a penetration temperature differed by more than 2°C from the nominal value, the temperature is noted and the data no longer listed.

	Penetration 4			Penetration 5			Penetration 6			Penetration 7		
Test case	*t* (s)	χ_8 (g m^{-3})	$\frac{\chi_8}{\chi_0}$	*t* (s)	χ_{11} (g m^{-3})	$\frac{\chi_{11}}{\chi_0}$	*t* (s)	χ_{14} (g m^{-3})	$\frac{\chi_{14}}{\chi_0}$	*t* (s)	χ_{17} (g m^{-3})	$\frac{\chi_{17}}{\chi_0}$
1	633	0.61	0.77	753	0.10	0.13	896	0.23	0.29		+4°C	
2	632	0.44	0.25	832	0.35	0.20		−1°C				
3	612	0.00	0.00	776	0.00	0.00		−1°C				
4	638	0.03	0.06	814	0.31	0.60	984	0.28	0.54	1167	0.21	0.40
5	634	0.48	0.49	784	0.36	0.37	952	0.26	0.27	1117	0.32	0.33
6	648	0.15	0.22	829	0.09	0.13		+1°C				
7	644	0.00	0.00	820	0.00	0.00	998	0.00	0.00		−2°C	
8	630	0.00	0.00	816	0.00	0.00	1012	0.00	0.00	1169	2.36	2.54
9	648	0.12	0.12	835	0.16	0.16		+1°C				
10	632	0.00	0.00	854	1.21	0.71		−2°C				
11	630	0.17	0.19	797	0.11	0.12	983	0.03	0.03	1193	0.34	0.38
12	638	0.27	0.48	846	0.12	0.21	1011	0.05	0.09	1145	0.00	0.00
13	671	0.35	0.47	840	0.15	0.20	1020	0.19	0.25		−1°C	
14	677	0.33	0.59		−3°C							
15	620	0.12	0.15	798	0.13	0.16		0°C				
16	634	0.43	0.38	801	0.13	0.12	967	0.54	0.48	1163	0.63	0.56
17	677	0.30	0.28	851	0.40	0.37	1029	0.16	0.15	1213	0.32	0.29
18	668	0.25	0.42	863	0.58	0.98	1046	0.09	0.15	1217	0.33	0.56
19	664	0.03	0.25	840	0.08	0.05	1014	0.01	0.01	1193	0.18	0.11
20	658	0.22	0.23		+1°C							

cloud, it is likely that no meaningful statement on LWC decay can be made.

The following sections will present i) a recalculation of the decay constant for several different data sets; ii) an examination of the statistical support for an exponential representation of the decay of cloud LWC; and iii) an alternative method of calculating cloud top lifetime.

3. The evidence for an exponential decay of LWC

Cooper and Lawson concluded that an exponential decay of cloud LWC with a time constant (τ) of 832 s was an adequate representation of the experimental data. This was calculated by assuming a model of the form $\chi/\chi_0 = e^{bt}$ (where $\tau = -1/b$). Results of a recalculation using this model and one of the form $\chi/\chi_0 = e^{a+bt}$ [where $\tau = -(1 + a)/b$] for several different data sets are discussed below. The results are given in Table 2.

a) *Data set 1:* For each of the 20 test cases (i.e., clouds) the values of χ/χ_0 at every time step until $\chi/\chi_0 = 0.0$ are included. This means that up to one value of $\chi/\chi_0 = 0.0$ can be included in the set for each test case. Twenty points are assigned a ratio of one at $t = 0$. Such an arrangement will result in a sample size of 111. For cloud 8, $\chi = 0.0$ at $t = 630$ s. However, a value of $\chi = 2.36$ is reported at $t = 1169$ s, resulting in a value of $\chi/\chi_0 = 2.54$. This value has not been included in the data set. On the other hand for cloud 16, χ is reported zero at 445 s and nonzero for all the next time steps. The subsequent nonzero values of χ/χ_0 have been included in the data set. Data set 1 is complete and includes the important points that are obtained when the measured LWC falls to zero ($\chi = 0$ and $\chi/\chi_0 = 0$). However, it cannot be used if one fits an exponential function to the data.

b) *Data set 2:* All points of data set 1 excluding those with $\chi/\chi_0 = 0.0$. The resulting sample size is $n = 105$.

c) *Data set 3:* All points of data set 1 excluding those with $\chi/\chi_0 < 0.1$. The resulting sample size is $n = 95$. Likely, this is the data set used by Cooper and Lawson (1984).

Using the above data sets, a regression analysis was performed assuming exponential models of the forms $\chi/\chi_0 = \exp(a + bt)$ and $\chi/\chi_0 = \exp(bt)$. The second model specifies $\chi/\chi_0 = 1$ at $t = 0$, which is the situation as defined. The first model has been assumed in order to see to what degree the measurements support such a condition. Simple linear models with χ/χ_0 as the independent variable and time as the only dependent variable (such as $\chi/\chi_0 = a + bt$) could have been used as well, but such linear models will always predict that $\chi \longrightarrow 0$ at a specific time irrespective of the value of χ at $t = 0$. This physical impossibility would suggest that an exponential decay is the more realistic consideration of the two.

Table 2 gives results from the regression analyses. For each data set and each assumed model the regression coefficients a and/or b, the coefficient of determination r^2, and the decay constant τ are given. The coefficient of determination is defined as:

$$r^2 = 1 - \sum (y - \hat{y})^2 / \sum (y - \bar{y})^2,$$

where $y = \ln(\chi/\chi_0)$. The bar indicates the mean and the hat the expected value of y. The arithmetic value of r^2 gives the percentage of the variation of y in time that is explained by the regression equation. The decay constant τ is the time at which the initial cloud water has decreased by a factor of e^{-1}.

Two conclusions can be drawn from Table 2. First, for each data set there are no significant differences in the goodness of fit (as judged by r^2) or in the magnitude of the decay constant resulting from a change of models. Second, in none of the cases considered is the decay constant equal to CL's value of 832 s. The calculated values of τ range from 500 to 690 s. The most acceptable decay constant is probably 560 s resulting from the more complete data set 2 and an exponential model of the form $\chi = \chi_0 e^{bt}$. This value is 272 s (4.5 min) shorter than the value of CL.

This difference in calculated decay constants is physically very significant since short cloud lifetimes are felt to play a negative role in rain production from HIPLEX-1 clouds. Cooper and Lawson's decay constant of ≈ 14 min means the average maximum 1-km LWC of 1.05 g m^{-3} would fall to (e^{-1}) 0.39 g m^{-3} in 14 min, to $(2e)^{-1}$ 0.14 g m^{-3} in 28 min, and to $(3e)^{-1}$ 0.05 g m^{-3} in 42 min. These times in fact represent substantial growth times when one considers that they are meant to represent only the upper portion of the cloud. For comparison, from Table 2 for the model $\chi = \chi_0 e^{bt}$ we obtain from data set 3 a drop in LWC to e^{-1} in 11.5 min, to $(2e)^{-1}$ in 23 min and to $(3e)^{-1}$ in 34.5 min. For the larger data set 2 we obtain even smaller values, as the LWC drops to e^{-1} in 9.5 min to $(2e)^{-1}$ in 19 min and to $(3e)^{-1}$ in 28.5 min. The value of the decay constant is clearly dependent on the data set used. The most useful decay constant will be the one that most clearly represents the reality of the phys-

Table 2. Results of decay constant calculations using two different data sets. See the text for a description of the data sets. Data set number 2 has 105 points; data set number 3 has 95 points.

Model	Data set 2	Data set 3
$\frac{\chi}{\chi_0} = \exp(a + bt)$	$a = -0.305$ $b = -1.39 \times 10^{-3}$ $r^2 = 0.25$ $\tau = 500$ s	$a = -0.203$ $b = -1.19 \times 10^{-3}$ $r^2 = 0.36$ $\tau = 670$ s
$\frac{\chi}{\chi_0} = \exp(bt)$	$b = -1.79 \times 10^{-3}$ $r^2 = 0.22$ $\tau = 560$ s	$b = -1.45 \times 10^{-3}$ $r^2 = 0.33$ $\tau = 690$ s

ical observations. This is discussed further in Section 4.

A final point: The data can be divided into two parts, those shown in Table 1a for −8°C and those shown in Table 1b for −5°C. Considering the data points of data set 3 that correspond to χ_2/χ_0 and χ_5/χ_0 (i.e., a constant altitude), we calculated a sample correlation coefficient $r = -0.03$. We then added the 20 points that correspond to $t = 0$ and $\chi_0/\chi_0 = 1$ and we found that $r = -0.54$. We finally added (from Table 1b) the rest of the data points and we calculated that $r = -0.60$. These results indicate that most of the sample correlation results from considering that at $t = 0$, $\chi/\chi_0 = 1$. Apart from that, the points at either the first flight level or the second are virtually uncorrelated, with the correlation improving only slightly by taking the two parts together.

4. Cloud top lifetime calculation

An alternative to representing the change in LWC in the HIPLEX-1 clouds by a decay constant is to treat the data in the same manner as Schemenauer and Isaac (1984) dealt with their calculations of cloud top lifetime.

Schemenauer and Isaac (1980, 1984) introduced the concept of a calculated cloud top lifetime based on the measured rate of change of liquid water content (LWC) at a constant altitude. The concept followed was that a cloud was studied for as long as possible at a constant altitude and an average rate of change of LWC in g m^{-3} min^{-1} was calculated for each cloud. This is b in the expression $\chi = \chi_0 + bt$. Then the mean first pass LWC for the field season was divided by the mean rate of LWC change. This produced a time (t_L) for the cloud top LWC to decrease to 0.0 g m^{-3}. This value ($t_L = \overline{\chi_0}/\bar{b}$) is the cloud lifetime. The time required for a decrease to any other desired LWC can also be calculated. This is a simple concept, it is easy to apply to other data sets, it makes geographical and temporal comparisons straightforward and it produces specific times for the disappearance of the cloud top that can be compared to actual aircraft observations.

This technique avoids one of the major problems of an exponential fit to the data. The exponential model and the associated decay constant cannot be used to predict a realistic drop in LWC to 0.0 g m^{-3}. In addition, when fitting the exponential model to the data, all of the observations where the LWC fell to zero during the cloud study are neglected! That is, the actual measurements of what one is trying to describe are not used.

Table 3 shows the results of the cloud top lifetime calculation using the data as presented in Table 1a. Results are given for 1979 and 1980 separately and combined together. The values for the two years are not significantly different and the use of the combined value is probably appropriate. The calculations apply only to the data in Table 1a at a relatively constant altitude in each cloud corresponding to a nominal temperature of −8°C. The mean maximum 1-km LWC value of 1.05 g m^{-3} will decrease at a mean rate of −0.072 g m^{-3} min^{-1}. This would result in the disappearance of cloud water (0.0 g m^{-3}) at −8°C in 15 min. Fifteen minutes can therefore be considered the cloud top lifetime for this project period and location. *A decay constant is not a comparable number* (see Section 3).

Cooper and Lawson describe the HIPLEX-1 aircraft measurements as follows, ". . . none of the measured values of AWC8 was above 0.1 g m^{-3}. . . ." The 4-km average LWC 8 min after seeding is AWC8 (≈10.5 min after the pretreatment pass). In addition, the maximum 1-km average LWC had a mean value of "only 0.25 g m^{-3}" 8 min after seeding. From Table 1b the mean value of χ_8 is 0.22 ± 0.18 g m^{-3}. The observations are compared to the calculated values in Table 4.

In Table 4 the best approximation of the measured mean maximum 1-km average LWC comes from applying the rate of change of LWC from the lifetime calculation. The second best one is the second exponential fit of Table 2 using data set 2. The poorest prediction shown is obtained using CL's decay constant of 14 min. The latter is too slow in reducing the cloud LWC, requiring, for example, 21.5 min to reduce the peak LWC to 0.22 g m^{-3} instead of the observed 10.5 min.

It is harder to compare calculated values to the measured response variable AWC8. The variable AWC8 is a 4-km average LWC that effectively encompasses the entire original cloud width of ≈3.5 km (Cooper and Lawson, 1984). Rates of change of LWC or decay constants based on maximum 1-km values are not appro-

TABLE 3. Representative cloud top lifetimes at −8°C calculated in the manner of Schemenauer and Isaac (1984). The mean maximum 1-km average LWC (χ) (± one standard deviation) and the mean rate of change of LWC ($d\chi/dt$) are calculated from Table 1a. Values are given for each year separately and the two field seasons combined.

			Cloud top lifetime to			
Year	Mean χ (g m^{-3})	Mean $\frac{d\chi}{dt}$ (g m^{-3} min^{-1})	0.0	0.1 (min)	0.25 g m^{-3}	Number of clouds
1979	1.12 ± 0.59	−0.084 ± 0.071	13	12	10	12
1980	0.95 ± 0.36	−0.054 ± 0.049	18	16	13	8
1979/80	1.05 ± 0.51	−0.072 ± 0.064	15	13	11	20

TABLE 4. Comparison of the HIPLEX-1 aircraft observations to the cloud top lifetime calculation from Section 4 and the results from the decay constant calculation of Cooper and Lawson (1984), and the decay constant calculation in this note for model 2, data set 2. χ_8 is the mean maximum 1-km LWC 8 min after seeding. AWC8 is the 4-km average LWC, 8 min after seeding ($\approx$10.5 min from pretreatment). The value with the asterisk (*) was obtained from Schemenauer and Isaac (1984) using a mean first pass LWC and a mean rate of change of LWC for the two years.

			Decay constant ($g m^{-3}$)	
Parameter	Observed ($g m^{-3}$)	Lifetime	Cooper and Lawson (1984)	Present study
χ_8	0.22	0.29	0.49	0.34
AWC8	<0.1	0.0*		

priate for predicting AWC8. However, Schemenauer and Isaac (1984) produced cloud lifetimes for the HIPLEX-1 area based on LWC values averaged across the entire cloud width. Their data set (not HIPLEX-1 clouds) contained clouds with a mean width on the first pass of $\approx$2 km at -7°C versus $\approx$3.5 km at -8°C for the HIPLEX-1 clouds. Their mean two year first pass LWC of 0.5 g m^{-3} decreased at a mean rate of 0.06 g m^{-3} min^{-1} resulting in a predicted disappearance of a cloud in about 8.5 min from the first penetration. This is compatible with the AWC8 value quoted above.

5. Discussion and conclusions

Three recent papers (Smith *et al.*, 1984; Mielke *et al.*, 1984; Cooper and Lawson, 1984) have carefully described the design and results of the HIPLEX-1 weather modification project (Montana). The results were similar in at least one respect to those of Isaac *et al.* (1982) for two locations in Canada. It was found in both countries that the persistence of cloud liquid water in the supercooled portion of cumuli was an important factor in determining whether the natural or seeded clouds rained. This was mentioned in the early results from the Canadian projects (Isaac *et al.*, 1978, 1979) but it wasn't until 1980 (Schemenauer and Isaac, 1980) that quantitative lifetime calculations were presented for three project areas and a plea made for a common representation of cloud top lifetime that could be used to examine geographical and seasonal differences. Schemenauer *et al.* (1981) and Schemenauer and Isaac (1984) reemphasized the importance of cloud top lifetimes in weather modification experiments. The present paper continues the discussion by means of an examination of the HIPLEX-1 data in a search for the best means of representing the decay of cloud liquid water in the HIPLEX-1 clouds.

The basic HIPLEX-1 LWC data was abstracted from Cooper *et al.* (1982a,b), the maximum 1-km LWC averages (χ) for each aircraft pass were normalized to that on the first pass (χ_0) and the results presented here in Tables 1a, b. A simple linear representation of the ratio ($\chi/\chi_0 = a + bt$) or a simple polynomial are not applicable since they lead to the requirement that all clouds reach zero LWC at the same time regardless of initial LWC. Linear models with χ/χ_0 as the independent variable and with more than one dependent variable (e.g., $\chi/\chi_0 = \chi_0 + bt$) or similar linear models with χ as the independent variable (e.g., $\chi = \chi_0 + bt$) would not present the above problem. An exponential fit of the form $\chi/\chi_0 = \exp(a + bt)$ or $\chi/\chi_0 = \exp(bt)$ avoids the problem of a common time for zero LWC but creates others. Using the first formulation one will obtain a nonzero value of a when fitting the data. This is in disagreement with the conditions that by definition $\chi/\chi_0 = 1$ and $a = 0$ at $t = 0$. This difficulty is avoided in the second model by forcing the best fit exponential line to go through $\chi/\chi_0 = 1$ at $t = 0$. The exponential model suffers by not using measured values of $\chi = 0$ which are physically very important and it cannot realistically predict the time when $\chi = 0$ (the lifetime). Both of these problems are avoided by utilizing an approximation that accepts data down to some arbitrary value of χ as $\chi \rightarrow 0$.

Table 2 shows the results of calculating an exponential fit to the data using the two forms discussed above and two different data sets created from Table 1. Values of the decay constant (τ) range from 500 to 690 s. The value of 832 s (14 min) quoted by Cooper and Lawson (1984) was not reproduced. The most representative value of τ is probably 560 s (9.5 min) obtained from a model of the form $\chi/\chi_0 = \exp(bt)$ using all nonzero values of χ/χ_0. This results in a much faster decay of LWC than that postulated by Cooper and Lawson and produces results that are in better agreement with the experimental observations. There is considerable noise in the data and this is reflected in the low value of the correlation coefficient (0.47) and the coefficient of determination (0.22). This is, probably in part, due to the use of data from two levels, -8° and -5°C, but is mostly due to the inherent variability in the data. Limitations of the data are discussed in Section 2 and the goodness of the exponential fit in Section 3.

The closest representation of the aircraft measurements is produced by using a cloud top lifetime calculation of the form ($\chi = \chi_0 + bt$) given by Schemenauer and Isaac (1984). This gives a representative lifetime of 15 min (see Section 4) for the maximum 1-km LWC over the two year project period. Only measurements at -8°C were used to obtain this value and all observations, including zeros, were utilized. Not only does this calculation of the rate of change of LWC produce a faster initial drop in LWC in conformance with the observations but it results in a finite lifetime (15 min) for the maximum LWC region rather than simply a drop to e^{-1} of the initial value in a time τ.

The utility of a number that characterizes the persistence of cloud LWC is quite evident; the method of arriving at this number is not so clear. This is, at least in part, due to the small number of clouds that make up most field data sets and to the natural variability of cloud LWC. This paper has shown some of the different results that may be obtained from a common initial data base. The final choice of a definitive way of calculating cloud top lifetime may have to await the testing of these and other techniques on a wider set of field measurements.

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