

## Cloud liquid water content responses to hygroscopic seeding of warm clouds

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**The cloud liquid water content (CLWC) data in time and space from a total of 96 pairs of target (T) and control (C) experiments were analysed in this study to compare the responses of CLWC to hygroscopic seeding of warm clouds. Our results of various approaches taken for this analysis have indicated significant modifications in the CLWC for the T clouds as against C clouds.**

**Analysis of changes in CLWC in the T clouds after and before seeding has pointed out their increasing trend of values with increment in the number of seeded traverses in most cases. These results have shown that CLWC in the T clouds increases following the seeding treatment in the range 9–26%. Similar comparisons in the C clouds have indicated obvious diminution in CLWC that lies in the range 5–11%. These results clearly indicate the influence on microphysical growth and decay of such clouds that arises from hygroscopic seeding and not seeding of warm clouds. Analysis of spatial responses of CLWC to seeding has shown that the optimum effect of seeding may be achieved for a suitable cloud in the altitude range 5750–6250 ft (asl) in the Pune area. It is believed that this study has provided adequate support in favour of the hypothesis of hygroscopic seeding of warm clouds.**

A recent review<sup>1</sup> on the possible effects of hygroscopic cloud seeding experiments to enhance the condensation-coalescence process and rainfall in multicelled cumulus and stratocumulus clouds has summarized the results of almost all of the work related to cloud seeding experiments the world over. These summaries have provided unanimous indications of some success of these experiments. Although the evidences produced in their results are not fully convincing, it seems that most of them have shown possible effects that are consistent with those expected from hygroscopic seeding, i.e. (i) cloud droplet distributions have been found to be broader than what would have been naturally; (ii) echoes may have formed sooner, when otherwise they may not have; and (iii) some indications of dynamic effects in the form of higher cloud tops and larger growth rates. The realization of most of these effects can also be established through the responses of cloud liquid water content (CLWC), since all of these are ultimately linked with CLWC.

A 11-year experimental programme of air-borne cloud seeding experiments was in progress in the Pune (18°32'N, 73°51'E; 559 m asl) region, India, from 1973 to 1986 (except during 1975, 1977 and 1978). Some results in the early years of these experiments<sup>2-4</sup> and a few more at a later stage have appeared in the literature<sup>5-11</sup>. We also refer to a very recent study<sup>12</sup> of these experiments. All these studies, including the recent one, are related to physical evaluation of seeding effects, rainfall data analysis, microphysical, dynamical and electrical responses, chloride and sodium ion concentrations of rain and cloud water, and numerical simulation of warm rain processes of the cloud seeding experiments mentioned above.

The possible successful results of the studies mentioned above have motivated us to look back at the CLWC measurements made during the 6-year period (1981–1986) of above experiments. During these six years, the autographic records of CLWC, synchronized with the Johnson–Williams (J–W) liquid water content meter, were successfully obtained. We do not find a report on the systematic study of these CLWC measurements in the works mentioned earlier. The warm cloud seeding hypothesis used in the present study is the same as that used by other scientists elsewhere<sup>1,13-15</sup> and is based on the premise that seeding of clouds with giant size (> 10 μm) hygroscopic nuclei or with water spray will enhance the collision and coalescence of existing droplets sufficiently, to lead to precipitation in a cloud which would otherwise produce no precipitation or produce precipitation belatedly. The objective of this study is to report the findings on responses of CLWC to cloud seeding during the experiments conducted during the six years. It is believed that this study may provide additional support in favour of the hypothesis of hygroscopic seeding of warm clouds.

Since its inception, the term hygroscopic seeding has taken on slightly different meanings depending on the experimental design, type of seeding material used, and the type of cloud that was the subject of experimentation<sup>1</sup>. However, in almost all studies the ultimate goal was to enhance rainfall by somehow promoting the condensation-coalescence process. Any modification in this process may therefore have implications on the origin and evolution of precipitation processes involving overall cloud dynamics from the redistribution of energy in the form of latent heat released associated with condensation. By the term modification of warm cloud processes, we mean the influence that the seeding has on the condensation-coalescence process to enhance the production of raindrops. As quoted in the literature, seeding may help to initiate condensation-coalescence and drop-size growth, and in turn an increase in the CLWC, when otherwise it would not have naturally.

As discussed at length, various warm cloud seeding techniques, such as the direct introduction of appropri-

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ately-sized cloud condensation nuclei (CCN) or rain-drop embryos sprays, have been commonly used in practice<sup>1</sup>. The basic concept of the introduction of these larger CCN is not to allow the activation of the smaller natural CCN that lower the total concentration of initial droplets, but to promote the broadening of their initial droplet spectra. Introduction of the CCN thus initiates condensation and accelerates the coalescence process. It has been reported<sup>3,12</sup> that the 11-year programme of airborne cloud seeding experiments, mentioned earlier, used a CCN mixture of common salt and soapstone in the ratio 10 : 1 with a mode diameter of 10 microns.

Treatments of these nuclei were delivered at nearly constant altitude of a few hundred feet above cloud base, dispersing them at a rate up to 10 kg per km of flight path. More details of these experiments, such as location of experimental area, average meteorological conditions, seedability criterion, etc. are furnished below.

The experimental area is located on the lee-side of the Western Ghats in the Deccan plateau region at an altitude about 550 m asl. It is about 40 km east of Pune (18°32'N, 73°51'E, 559 m asl). The experimental area is perpendicular to the westerly monsoon flow. Rain seems to fall primarily from the clouds with their tops below 3–4 km. Once the monsoon is established, cumulonimbus clouds are practically absent. It has been reported<sup>15</sup> that the freezing level in the experimental area during the summer monsoon months is at about 6 km and large majority of the clouds do not reach higher than 5 km. Hence, the dominant rain-forming process in these clouds is the collision–coalescence and break-up.

A cross-over design having two sectors with a buffer between them has been adopted and these are North, South and buffer sectors. The area of each sector is 1600 sq km.

The classification of the seedable days has been based on the following criteria: (i) forecast amount of low clouds; (ii) upper level winds; (iii) special radiosonde observations carried out at Pune a few hours before the commencement of actual seeding; (iv) special current weather observations particularly in respect of cloud formation and development, recorded at two locations (one each in North and South sectors). A day has been considered as seedable when the forecast amount of low clouds was 3 okta or more, westerly wind speed was not exceeding 20 knots up to a height of 3 km asl, relative humidity was more than 75% in the lower atmosphere and the synoptic conditions were favourable for the formation of low clouds.

The 11-year warm cloud seeding experiments in the Pune region were carried out during the four months (June–September) of the Indian south-west monsoon season. The experimental area as well as the time of seeding operations during all these years remained the same. Most of the time these experiments were carried

out in the afternoon hours (between 1400 and 1600 IST). More details regarding these experiments are available elsewhere<sup>5–10,12</sup>.

It is true that no two clouds at any time are identical, they could be only like or similar. Incidentally, in this regard, it is a matter of privilege to mention that the aircraft model (DC-3, Dakota) and the captain of the aircraft remained the same throughout the 11-year programme of the experiments. In many matters of decision-making relating to the conduct of the experiments, the logistic support and the expertise in navigation of the captain were very useful. Comparisons between the physical features of the clouds such as nearly the same cloud base level (about 5500 ft asl or higher) and horizontal extent (about 5–7 km), instantaneous value of cloud liquid water content of about  $0.5 \text{ g m}^{-3}$ , and vertical thickness of 1 km, facilitated the selection of two similar clouds. Following the above guidelines, when isolated cumulus/stratocumulus cloud structures were present in the experimental area, one such cloud ensemble was identified and chosen for cloud seeding operations. In almost all operations, five successive traverses through the cloud were made at nearly constant altitude of a few hundred feet above the cloud base. The time lapse in the subsequent traverses (i.e. from traverse I to traverse V) of each operation was nearly 5 min. The maximum duration of each traverse was approximately 3 min. The cloud seeding operations would commence from the 3rd traverse of the cloud and would continue until the end of the 5th traverse. The seeded cloud was termed as target (T) cloud. After the completion of the seeding exercise, a search for a C cloud, having cloud physical features comparable to T cloud, was made. Identical repeated traverses through the C cloud were also made, but without cloud seeding. The unseeded cloud was termed as C cloud. This complete exercise would form a pair of T/C experiments, and the time required for this complete exercise was about one and half hours.

During the six-year period from 1981 to 1986, 96 pairs of experiments were conducted in the Pune area. Out of these, the CLWC data were available on 88/82 T/C cases, as on the remaining days the data was not be available due to some technical difficulties. The present study is focused on the observations of CLWC from these experiments and the documentation of differences in the responses of CLWC due to seeding. The differences in the responses of CLWC due to seeding have been worked out and the results are presented.

CLWC was measured by employing a Johnson–Williams (J–W) hot-wire liquid water content meter. Earlier studies<sup>16,17</sup> reported that this instrument measures the CLWC that is contributed by cloud droplets of diameter  $\leq 30 \mu\text{m}$ . For obtaining a continuous record of CLWC, the output of the CLWC meter was amplified by using an electronic circuit consisting of an opera-

tional amplifier (Burr-Brown, USA, Model 3234/15 FET) and the signal from this system was recorded on a direct writing 0–1 mA, Easterline Angus, strip chart recorder. On each flight day of the aerial cloud seeding experiments, the ground calibration of the CLWC meter was made before the flight by using a dummy sensing head, also supplied by the same company (J–W, USA). During an experiment the CLWC meter readings were continuously monitored and spot readings were also simultaneously noted on the strip chart records. This practice was of prime importance and regularly followed since it has facilitated the comparison of the records of CLWC with those of the J–W meter readings. A large number of such comparisons have shown that the autographic chart records of CLWC matched well with the meter readings. The error in this recording system was  $\leq 5\%$ . The mean value of CLWC during each traverse of T and C clouds was worked out by picking up the data points at every 5 s interval. Hence for each traverse of T/C cloud, the number of CLWC samples used in the present study was about 36. Sample records of time evolution of CLWC on two days (25 August 1984 and 4 August 1986) of target and control experiments are shown in Figure 1 *a* and *b*.

Table 1 shows the yearwise (1981–1986) mean values of CLWC and their standard deviations for the traverses 1–5 of the T/C experiments. These means are the average of mean CLWC from a number of experiments during the individual years.

Data (Table 1) from traverses 1–5 of the T/C experiments are analysed in three different ways to study the response of CLWC to seeding.

(i) Percentage change in CLWC in traverse 4 with respect to traverse 3 is worked out for each year for the T and C experiments, i.e. we worked out

$$\frac{\text{CLWC in traverse 4} - \text{CLWC in traverse 3}}{\text{CLWC in traverse 3}} \times 100.$$

The mean result for the six years showed that CLWC in traverse 4 of target experiments increased by 9% with respect to traverse 3. Similar analysis in case of control experiments showed that CLWC decreased in traverse 4 by 5% with respect to traverse 3. A similar analysis by considering

$$\frac{\text{CLWC in traverse 5} - \text{CLWC in traverse 3}}{\text{CLWC in traverse 3}} \times 100,$$

showed that CLWC in traverse 5 increased by 23% with respect to traverse 3 in target experiments. Similar result, but for the control experiments showed that CLWC in traverse 5 decreased by 11% with respect to traverse 3.

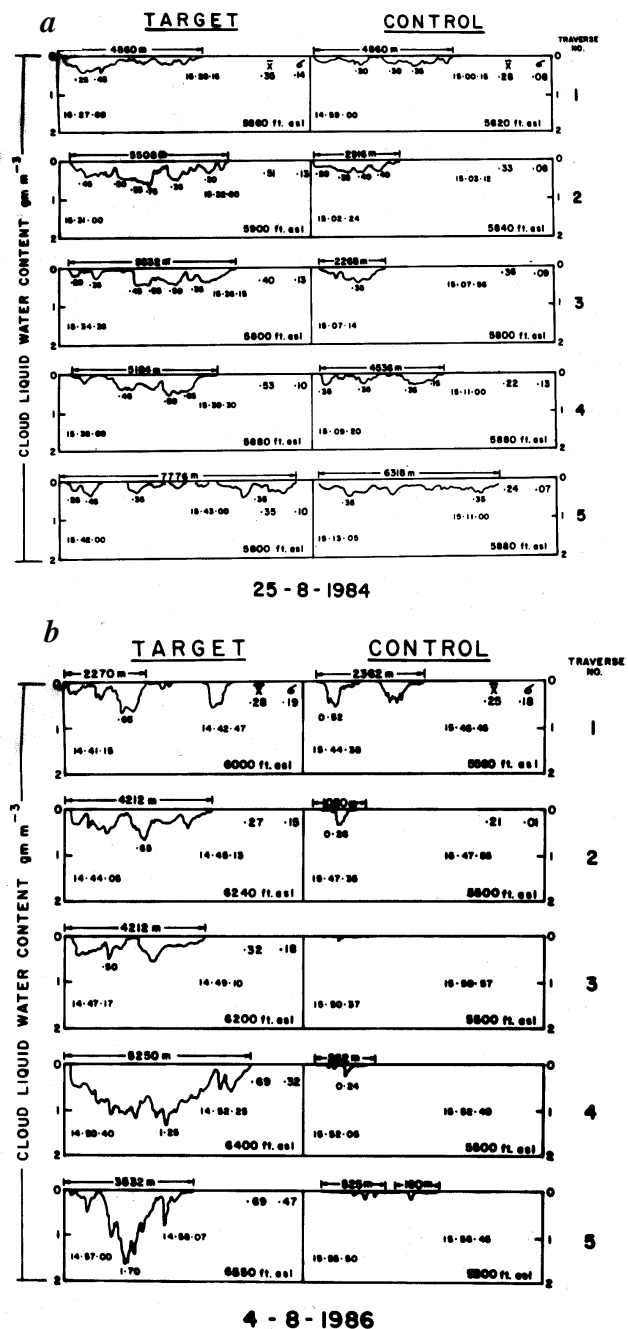


Figure 1. Sample records of time evolution of CLWC on (a) 25 August 1984 and (b) 4 August 1986 of target and control experiments. For each traverse the begin and end timings (IST), cloud height in feet asl, and cloud length in meters are shown. The right hand side of each curve shows average ( $\bar{x}$ ) and standard deviation ( $s$ ) of CLWC during the traverse. Numbers such as 0.65, 0.52, 0.50, 1.25, 1.70, ..., 0.50, 0.35, etc. along the CLWC records indicate the spot readings from the LWC meter.

(ii) We also worked out percentage change in mean CLWC of traverses (3 + 4 + 5) with respect to that of traverses (1 + 2 + 3) in target and control experiments. The six years' result showed that mean CLWC in traverses (3 + 4 + 5) of target experiments increased by 9% with respect to mean CLWC in traverses (1 + 2 + 3) of

**Table 1.** Yearwise (1981 – 1986) mean values and their standard deviations for the traverses 1 – 5 of CLWC for the target and control experiments

Year of experiment	No. of experimental days	Average cloud liquid water content ( $\text{g m}^{-3}$ ) in target and control traverses									
		Target traverse no.					Control traverse no.				
		1	2	3	4	5	1	2	3	4	5
1981	10	0.26 (0.09)	0.31 (0.14)	0.36 (0.20)	0.31 (0.13)	0.35 (0.18)	0.36 (0.24)	0.35 (0.12)	0.32 (0.24)	0.30 (0.09)	0.28 (0.14)
1982	17	0.45 (0.17)	0.44 (0.18)	0.43 (0.21)	0.48 (0.25)	0.56 (0.29)	0.44 (0.21)	0.42 (0.22)	0.40 (0.15)	0.39 (0.15)	0.33 (0.16)
1983	15	0.45 (0.14)	0.41 (0.16)	0.43 (0.15)	0.46 (0.14)	0.53 (0.21)	0.56 (0.34)	0.54 (0.21)	0.48 (0.23)	0.46 (0.17)	0.44 (0.18)
1984	23	0.48 (0.17)	0.48 (0.19)	0.47 (0.23)	0.53 (0.24)	0.64 (0.42)	0.35 (0.16)	0.42 (0.22)	0.43 (0.17)	0.40 (0.17)	0.41 (0.23)
1985	18	0.47 (0.11)	0.53 (0.13)	0.48 (0.11)	0.55 (0.17)	0.53 (0.13)	0.50 (0.20)	0.53 (0.21)	0.52 (0.18)	0.49 (0.20)	0.45 (0.23)
1986	13	0.42 (0.13)	0.46 (0.15)	0.40 (0.14)	0.49 (0.20)	0.56 (0.25)	0.39 (0.13)	0.39 (0.10)	0.34 (0.13)	0.36 (0.11)	0.38 (0.10)
Total 96											

target experiments. Similar result, but for control experiments showed a decrease in CLWC by 12%.

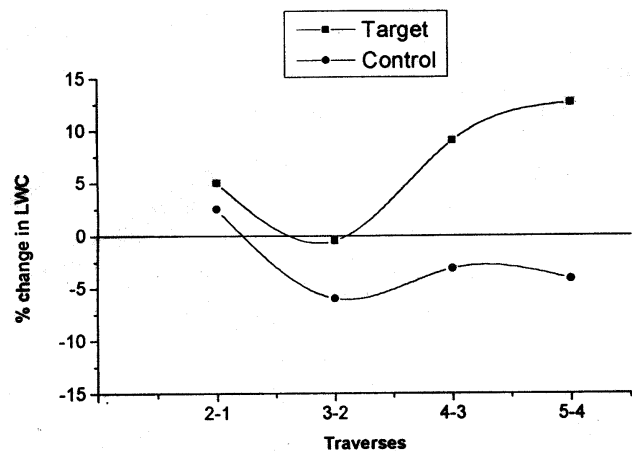
(iii) We also worked out percentage change in CLWC by considering

$$\frac{\text{CLWC in traverse 5} - \text{CLWC in traverse 1}}{\text{CLWC in traverse 1}} \times 100,$$

for both the categories of experiments. Net result for the six years showed that CLWC in traverse 5 of target experiments increased by 26% with respect to traverse 1. In control experiments CLWC in traverse 5 decreased by 11% with respect to traverse 1.

We have taken three different approaches in our method of analysis to study the responses of CLWC to cloud seeding. All our results suggest that CLWC in target experiments increases as the traverse number after commencement of seeding increases. This increase in CLWC is observed to be in the range 9–26% for the target (seeded) clouds; while the control (unseeded) clouds showed a decrease in the range 5–12%. This positive and negative response of CLWC in T/C experiments is also verified by plotting the mean percentage in CLWC during the subsequent traverses, i.e. Tr(2–1); Tr(3–2); Tr(4–3); and Tr(5–4), by using the data from Table 1; this is shown in Figure 2. The curves drawn through these data points self-explain the response of CLWC to seeding. We note that this effect is noticeable from the start of seeding, i.e. from Tr3.

From Figure 2 it can be seen that for the first two traverses the curves for T and C clouds show in-phase relation of CLWC, but from the third traverse onwards the anti-phase relation is more pronounced. The correlation coefficient between T and C clouds was worked out and it was observed to be 0.219, which is not significant even at 50% level of significance. This implies that though there is growth of control clouds due to natural



**Figure 2.** Percentage response of CLWC during subsequent traverses for T/C clouds.

processes, there is more drastic enhancement in the growth of T clouds due to seeding. This observation is self-clear and consistent with the hypothesis of hygroscopic seeding of the warm clouds.

The results presented earlier have shown that the net response of CLWC to hygroscopic cloud seeding is consistently positive. Although this is true, it is worthwhile to see how many of these individual experiments during the six-year period yielded positive/negative response of CLWC to cloud seeding. This information is useful from the point of view of planning of these experiments. This particular aspect was verified by examining the positive or negative response of CLWC on individual experimental days, on which T/C operations were performed, i.e. on 88/82 days, respectively. Percentage increase/decrease in CLWC on each experimental day was worked out by considering the mean for the daily target and control experiments as shown below:

$$\frac{\text{CLWC in traverses (3+4+5)} - \text{CLWC in traverses (1+2+3)}}{\text{CLWC in traverses (1+2+3)}} \times 100.$$

The results of this analysis suggest that out of 88 target cloud cases, in 55 cases there is an increase in CLWC by nearly 29%, while 33 cases showed 14% decrease in CLWC. The result of 82 C cloud cases was almost in the opposite way.

The foregoing results of realizations of the responses of CLWC need to be verified from the study of some cloud physical parameters. Besides the CLWC, the commonly considered cloud physical parameters for the evaluation of seeding effects are cloud-droplets and raindrop size-distributions and their concentrations, concentrations of giant condensation nuclei (GCN), vertical air velocities and temperature, radar observations of clouds, and the rainfall itself. It is believed that the inclusion of the results of some of these parameters in the present work is necessary to supplement our results of CLWC analysis described earlier. Incidentally, we refer to a very recent publication by Murty *et al.*<sup>12</sup> for this purpose. This paper summarizes the achievements of the 11-year cloud seeding experiments near Pune and also describes the results of responses of some cloud physical parameters measured during these experiments. The highlights of the results from their study are given below.

The rainfall data relating to the area cloud seeding technique during the six years (1981–1986) showed an average rainfall (in mm) of 42.6/22.6, 6.5/2.1, 5.7/4.4, 10.2/6.2, 15.7/26.2, and 10.3/2.5 for the North seeded T/C sectors, respectively. Similar data for the south seeded T/C sectors showed an average rainfall of 21.3/30.9, 0.6/0.2, 3.3/1.2, 32.7/17.5, 11.4/4.4, and 1.7/5.9 mm, respectively. We note that the year-to-year

rainfall shows variation. But this variation is consistent in both (T and C) sectors. Here, it is important to note that the rainfall in the T sector, in most cases (seven out of 10), is substantially higher than in the control. The statistical evaluation of the rainfall data concluded that rainfall in the T sector increased by about 24 per cent. This result is significant at a 4 per cent level of significance. For more details on the rainfall analysis one may refer to Murty *et al.*<sup>12</sup>.

The results of other cloud physical parameters showed that the average concentrations of GCN in the T clouds were observed to be higher by about 2 particles per litre than in the C clouds. This difference in the concentration is considered to be of great importance in the initial development of precipitation-size drops<sup>18</sup>.

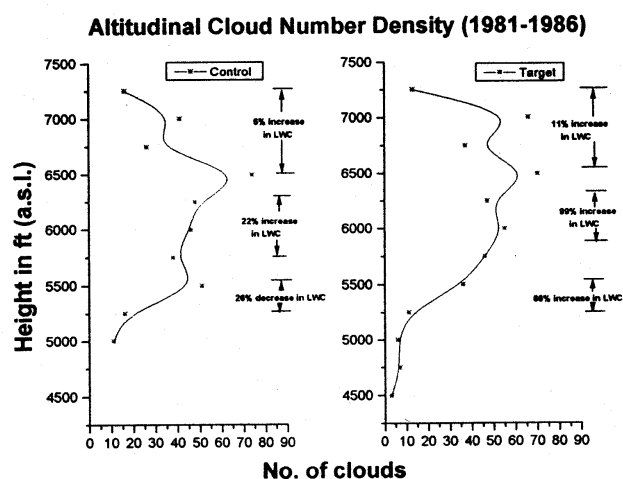
The cloud droplet spectra comparisons between C and T clouds showed an increase in the sizes of drops in all the size ranges. However the increase noticed in the larger-size range of the cloud drops as well as their number concentration in T clouds showed remarkable differences. This point of view becomes more clear from the comparisons of the average median volume diameter (MVD). In the C clouds MVD broadened from 9.8 to 10.0  $\mu\text{m}$ , while in the T clouds it changed from 8.7 to 11.7  $\mu\text{m}$ . The simultaneous measurements of the vertical air velocities and temperature in C and T clouds suggested clear association between the CLWC, vertical air velocity and temperature in any particular horizontal traverse.

It is believed that the results presented above are reasonably adequate, though not sufficient, to support our analysis and conclusion of CLWC responses to hygroscopic seeding of warm clouds.

The seeder aircraft flew at different altitudes (feet asl), usually ranging from 4500 to 8000 ft, in search of suitable clouds for conducting T/C experiments. The data on number of clouds and their altitudes were available from the notings made during traverses of the 96 pairs of T/C experiments (see Figure 1). There were a total of 390 clouds at different altitudes in the 96 experiments (see Table 1). The altitudes of these clouds were classified in 12 altitude intervals (4500–4750, 4750–5000, ..., 7250–7500) of uniform class width of 250 ft, beginning from 4500 ft, up to 7500 ft. The CLWC response for the T and C exercises of each cloud in these altitude intervals was worked out by considering:

$$\frac{\text{CLWC in traverse 5} - \text{CLWC in traverse 3}}{\text{CLWC in traverse 3}} \times 100.$$

The summary of this analysis is presented in Figure 3. It shows the altitudinal cloud number density of these clouds and net result of response of CLWC for the T and C events. A curve of best fit through the data points



**Figure 3.** Cloud number density in altitude thickness of 250 ft above 4250 ft asl up to 7500 ft asl and CLWC percentage response during T and C experiments.

is drawn by the cubic spline technique to describe the average altitudinal distribution of clouds in the Pune region. The curve shows three peaks, of which the peak around 6500 ft is more pronounced. It may be inferred that the most persistent altitude interval to experience cloud in this region is 6000–7000 ft. Percentage change in CLWC for the T and C events is also shown for some altitude intervals. The results of altitudinal response of CLWC shown in Figure 3 are self-clear. We note that the clouds in altitude range 5750–6250 ft offer the optimum results of cloud seeding in the target events, but not so for the control events.

The CLWC data in time and space from a total of 88/82 pairs of T/C experiments were analysed in this study to compare their responses to T and C events. Our results of various approaches taken for this analysis have indicated significant modifications in the CLWC for the T clouds as against C clouds.

Analysis of changes in CLWC in the T clouds after and before seeding has pointed out their increasing trend of values with increment in the number of seeded traverses in most cases. These results have shown that CLWC in the T clouds increases following the seeding treatment in the range 9–26%. Similar comparisons in the C clouds have indicated obvious diminution in CLWC that lies in the range 5–11%. These results clearly indicate the influence on microphysical growth and decay of such clouds that arises from hygroscopic seeding and not seeding of warm clouds.

Analysis of spatial responses of CLWC to seeding has shown that the optimum effect of seeding may be

achieved for a suitable cloud in the altitude range 5750–6250 ft (asl) in the Pune area. This study has allowed us to establish the adequacy of the hypothesis of hygroscopic seeding of warm clouds on temporal and spatial scales.

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