COMPARISON OF CLOUD TOWER AND UPDRAFT RADII WITH THEIR INTERNAL TEMPERATURE EXCESSES RELATIVE TO THEIR ENVIRONMENTS

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Abstract. Measurements of in-cloud temperature using reverse-flow thermometry were made in and around vigorous Thai supercooled convective clouds on 10 days in April and May 1993. Cloud vs. environment temperature differences were derived from these data and the differences were correlated with cloud and updraft radii at the level (6.5 km) of cloud penetration. This was done as a function of whether the clouds were isolated, growing in a group of comparably-sized clouds, or growing as "feeders" to cumulonimbus clouds. Positive correlations were noted in all instances, ranging from a minimum of 0.11 to a maximum of 0.48. The correlations were greatest for the comparisons of the temperature differences with updraft breadth. It was noted further that, for a given tower size or updraft width, the temperature differences were largest for clouds growing as feeders to cumulonimbus clouds. The implications of these findings to the design and evaluation of cloud seeding experiments are discussed.

This work was conducted under a contract with the Bureau of Reclamation as part of a program sponsored by the U.S. Agency for International Development to upgrade Thailand's weather modification capability.

1.0 INTRODUCTION

This paper is an outgrowth of continuing scientific discussions that the authors have had with a number of their colleagues. It is the contention of the authors that the life prognosis for a particular convective cloud depends in large part on where it lives and on its ancestry and that, in designing a convective cloud seeding experiment, one must take these factors into account. They argue further that, if one wants to detect the effect of seeding, it is best to select those clouds in which natural forcing is not so dominant that it overwhelms the expected signal from seeding. The seeded clouds may well become large and develop their own forcing. It is best, however, not to begin the seeding experiment with that process already well underway. Not everyone accepts these views.

As to a cloud's place of residence, Rosenfeld and Gagin (1989) have shown that, other factors being equal, clouds living in isolation produce about one-third the rain volume of those growing in clusters. As to ancestry, it is the authors' observation that relatively small convective clouds growing as feeders to gigantic parents are more likely to resemble those parents at maturity than a comparably-sized convective cloud growing in isolation some distance away, when it reaches maturity.

While working in Thailand on the Applied Atmospheric Resources Research Program (AARRP) (Woodley et al., 1994; Rosenfeld et al., 1994), the question arose whether simple measurements within a cloud might reveal differences that are related to a cloud's ancestry and place of residence. In earlier work, Woodley and Kreasuwun (1992) had used Thai cloud physics measurements to show a relationship between the visual appearances of Thai supercooled convective clouds and their maximum cloud liquid water contents. There was reason to hope, therefore, that meaningful science might come out of the current investigation, despite the relative simplicity of the Thai cloud physics platform.

Because clouds thrive on buoyancy (e.g., Simpson and Wiggert, 1969;1971), which is proportional to the difference between the internal cloud virtual temperature and that in its near environment, there was reason to start with the in-cloud temperature measurements. Positive differences (i.e., the temperature of the cloud exceeds that of its near environment) represent positive buoyancy and negative differences represent negative buoyancy. All clouds go through a natural cycle of growth and decay, having positive buoyancy during the growth phase and negative buoyancy during their decay phase. Other factors being equal, the larger the buoyancy, the larger the cloud will grow and the longer it will last.

One of the factors that inhibits cloud buoyancy, in addition to the water and ice load that the cloud tower is carrying, is the entrainment of drier air into the cloud circulation. This forces the cloud to evaporate some of its liquid water to saturate the entrained air. In doing so, the in-cloud air is cooled and buoyancy is decreased. It would seem intuitively obvious, therefore, that the larger the cloud the more protected its internal core should be from the deleterious effects of entrainment and subsequent evaporative cooling. If this is so, one would expect a positive correlation between the size of a cloud tower and/or the breadth of its internal updraft and the temperature excess that the cloud enjoys over its environment, while it is in its active growth phase. One might also expect the nature of the relationship to be a partial function of cloud ancestry and place of residence. These uncertainties are the focus of this paper.

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2.0 INSTRUMENTATION AND DATA

An Aero Commander 690B aircraft was provided to Thailand's AARRP effort under lease from Thai Flying Service. This turbo-prop aircraft was equipped with an airborne data acquisition and seeding system and served as the cloud physics platform and seeder for the program. In addition to standard avionics and flight instrumentation, the Aero Commander was equipped with the following: a Johnson-Williams-type liquid water content meter manufactured by Cloud Technology, Inc., a thermo-electric dew point hygrometer, a reverse flow thermometer, a Ball variometer and a satellite-based (GPS) navigation system that permits location of the aircraft to within 100 m. A forward-looking nose video camera was mounted in the cockpit and provided a continuous view of cloud conditions during flight through the extreme right side of the windshield. The liquid water hot wire and the Ball variometer were configured to measure water contents and draft speeds up to 6.0 gm/m^3 and 10 m/sec (2,000 ft/min), respectively. No Thai cloud had cloud water contents exceeding 6.0 gm/m^3 --- the largest was nearly 4.0 gm/m^3. Many Thai clouds did, however, have drafts exceeding 10 m/sec, particularly during pre-monsoon conditions.

Beginning on 15 April and continuing through June 6, 1993, flights of the Aero Commander aircraft were made at about 6.5 km MSL through visually-suitable clouds at temperatures ranging between -7 and -10°C, in order to access their internal characteristics. Most clouds were quite vigorous and appeared to contain primarily supercooled water. None of the cloud towers had been seeded prior to cloud penetration. At issue for this study were estimates of temperature, draft sign, breadth and strength and the diameter of the tower at penetration altitude.

Data from 10 flight days were subject to analysis: April 15, 18, 20, 21, 22, 23, 25, 29, May 4, 7, 8, and 9. Following each flight, the recorded data were processed to provide the times and locations of each cloud, the ambient temperature and dew point and the internal cloud temperatures, drafts and water contents. Pass times were converted to pass distances by multiplying by the aircraft true airspeed. In those instances when the aircraft passed through the center of the cloud bubble top --- determined from viewing the video tape from the aircraft nose camera --- the pass distance corresponds to a cloud diameter.

3.0 ANALYSIS PROCEDURES

Three assumptions and seven steps were necessary in relating cloud tower radii and updraft breadths to their internal temperature excesses relative to their environment:

Assumptions:

1. The clouds were penetrated in the prime of their lives such that one could expect to measure the maximum cloud-environment temperature excesses existent at the flight level,

2. The cloud vs. environment temperature difference can be estimated by taking the difference between the maximum measured in-cloud temperature and the average environmental temperature in the 60 sec prior to cloud penetration,

3. Cloud radius can be estimated by multiplying the time to traverse the tower by the aircraft true airspeed (in m/sec) and dividing by two.

Steps:

1. The cloud penetration data were analyzed to obtain cloud and environmental temperatures. Only those clouds whose maximum internal temperature exceeded the maximum environmental temperature in the 60 sec prior to cloud penetration were retained in the sample. Those that were eliminated were in their dying phase and would not satisfy Assumption 1.

2. The cloud vs. environment temperature difference was estimated according to Assumption 2. In instances when the aircraft either ascended or descended due to cloud drafts from a baseline flight pressure during a particular cloud pass, the temperatures were corrected back to the baseline pressure using moist adiabatic ascent or descent.

3. The video tapes from the aircraft nose camera were viewed to determine whether the aircraft penetrated near the center of the bubble/vortical cloud top. Only those clouds that were penetrated near their centers were retained in the sample.

4. Cloud radius was estimated as in Assumption 3.

5. Each cloud remaining in the sample was classified from the video tape as either growing alone (i.e., isolated), or growing in a group of similarly-sized towers, or growing as a "feeder" tower to or in association with a pre-existing cumulonimbus.

6. A scatter-graph was constructed and the correlation calculated, relating each cloud radius to its maximum cloud vs. environment temperature excess.

7. Upon the completion of step 6, a scatter-graph was constructed and correlation was calculated, relating updraft radius to the maximum cloud vs. environment temperature excess.

4.0 RESULTS

The results for step 6 are provided in Figure 1 in which the cloud classification (isolated, group or cumulonimbus) for each of the 81 data points is indicated. Despite the scatter, there appears to be a weak relationship between cloud tower size and the temperature excess that it enjoys relative to its environment. The linear correlation coefficients for cloud categories of isolated, group and Cb are 0.40, 0.35 and 0.11, respectively. Although each category does not explain much of the variance, linear best-fits were derived for each. Note that for a given radius the in-cloud temperature excess is a function of where the cloud is growing. For example, isolated clouds having a particular top radius have a smaller temperature excess than those of same size growing as feeders to Cbs. The most plausible explanation is that isolated clouds are more adversely affected by entrainment than those growing as a family or as a part of a Cb complex.

Although the results are physically reasonable, the point scatter of Figure 1 does not allow for much confidence in them. This scatter is likely due to at least the following factors: 1) not all clouds were penetrated in the prime of their lives, and 2) errors in radius estimation may have been made due either to inclusion or exclusion of extraneous cloud material as part of the subject cloud and/or to passage of the aircraft above the true cloud radius.

The next step (step 7) to refine the relationship further was to relate the in-cloud temperature excess to the portion of a given cloud pass that contained updraft. The steps 1 through 6 were repeated with the exception of step 4. In its place was substituted an estimate of the pass length in km that contained updraft. Division by 2 provided a crude estimate of updraft radius.

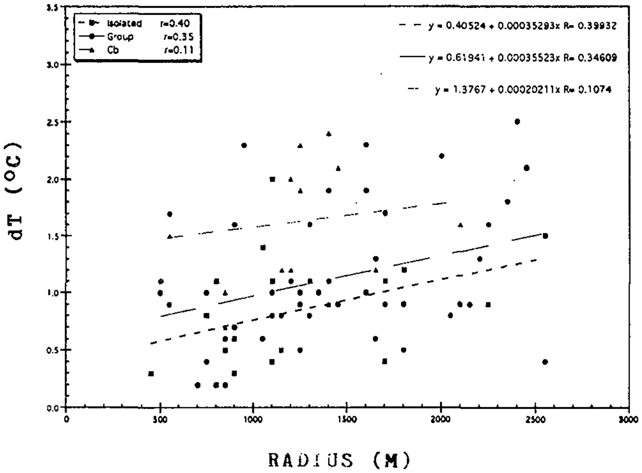

Figure 1. Scatter plot of cloud-top radius vs. the difference in temperature between maximum internal cloud temperature and the mean environmental temperature in the 60 sec prior to cloud penetration. The plot is stratified as a function of where the subject cloud was growing (i.e., isolated, within a group or in association with a cumulonimbus cloud). The linear best-fit lines and correlations are shown.

In some instances, this approach produced very different radius measurements from the original approach, especially when the cloud was large but inactive and without much updraft. In very active clouds, however, the updraft radius and the visual cloud-radius were nearly the same.

A new plot relating updraft radius to in-cloud temperature excess is provided in Figure 2. The scatter of the 81 data points is still great, but the correlations have improved to 0.45, 0.47 and 0.48 for the isolated group and Cb categories. The impressions gained from step 6 are reinforced in step 7. For a given category, the larger the updraft radius the larger the cloud vs. environment temperature excess. Further, the in-cloud excess is greater for a given cloud, if it is a part of Cb complex than it is if it is growing isolated from other clouds. These results are not surprising. Clouds thrive when growing in association with other clouds and they struggle if forced to fight for life alone.

5.0 DISCUSSION

This study has accomplished two things. First, it has demonstrated that there is indeed a positive relationship between the breadth of a cloud tower and its internal temperature excess relative to its environment. Second, it has established the importance of considering the "heredity" of a cloud in predicting its future. A cloud growing by itself without any family will have a harder time surviving in its hostile environment than a cloud that is growing within a large family, especially if some of those family members are very large.

Although this is intuitively obvious to some scientists, others argue that a cloud's familial history is of no importance in predicting its future. In their view, cloud towers of the same size, shape and internal structure at a given time can be compared over their lifetimes, regardless of their initial family circumstance. Such thinking is wrong, and it will create havoc when designing and evaluating an experiment that is focused on convective clouds.

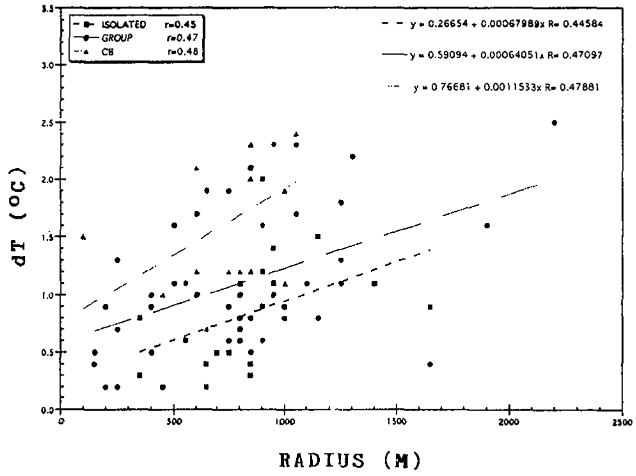

Figure 2. Scatter plot of the radius of the internal cloud-top updraft vs. the difference in temperature between maximum internal cloud temperature and the mean environmental temperature in the 60 sec prior to cloud penetration. The plot is stratified as a function of where the subject cloud was growing (i.e., isolated, within a group or in association with a cumulonimbus cloud). The linear best-fit lines and correlations are shown.

It is recommended, therefore, that a convective cloud seeding experiment be designed to ensure that clouds of comparable family history be selected for treatment and compared subsequently. If this is not possible, it is important that the clouds be partitioned after-the-fact as a function of their ancestry. Orphan clouds should be compared to orphan clouds and those that began in association with enormous extended cloud families should be compared only to other clouds with similar beginnings. Otherwise cloud ancestry will confound any attempt to get at the effect of seeding intervention.

6.0 REFERENCES

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