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COALESCENCE ACTIVITY IN TEXAS CLOUDS: THE INDEX OF COALESCENCE ACTIVITY AND FIRST-ECHO TOPS

Aldis Strautins
West Texas Weather
Modification Association
San Angelo, Texas

Todd Flanagan
South Texas Weather
Modification Association
Pleasanton, Texas

William L. Woodley
Woodley Weather Consultants
Littleton, Colorado

Abstract: This paper explores the use of the Index of Coalescence Activity (ICA) as a tool for operations and evaluation in Texas rain enhancement programs. Radar cross-sections through the first echoes were used to find the heights using the TITAN display software package from two WSR-74C 5-cm radars located in San Angelo and Pleasanton, respectively. Index of Coalescence Activity values were derived using the morning sounding data from three upper air stations. The ICA vs. the average height of First-echo Tops (FET) for a particular day was then plotted with calculated correlation coefficients of 0.62, 0.51, and 0.38 for the Del Rio, Corpus Christi, and Midland stations, respectively. The results show generally good agreement between the observed first-echo height and the Index of Coalescence Activity predicted First-echo Top except in one case, which is addressed in the text. The results of this study warrent continued research and preliminary use of the Index of Coalescence Activity as a forecasting and an evaluation tool in the cloud seeding operations of Texas.

1. INTRODUCTION

Perennial questions in all enhancement programs are whether, when, where and how cloud seeding is to be conducted. A question being faced currently in some of the Texas programs that have decided to employ hygroscopic seeding for rain enhancement in addition to conventional AgI methods is when either AgI or hygroscopic seeding is to be employed. This decision should be based on the cloud characteristics and seeding criteria. Based on current thinking, hygroscopic seeding should be used in clouds without an active coalescence process and AgI seeding should be used in clouds with some coalescence. Poor results might be expected if AgI is used on days when artificial CCN should be used and vice versa. Further, optimal results might be expected by appropriately using two rather than a single seeding technique.

The conceptual model for cold-cloud seeding proposes the release of latent heat from the freezing of supercooled water droplets to provide energy to the updraft portion of the cloud. (For a more in depth explanation of the Texas cold-cloud seeding model see Rosenfeld and Woodley, 1997.) Forecasting for the presence of supercooled water drops at the seeding height of -8°C to -10°C (5.5 km to 6.5 km) for warm season convection in Texas is vital information for cold-cloud AgI seeding. As shown during the 1989 Precipitation Augmentation for Crops Experiment (PACE) the L coalescence parameter that was first introduced by Mather et al. (1986) and further refined by Czys and Scott (1993) as an Index of Coalescence Activity (ICA), was found to be a good indicator for the presence of supercooled water drops larger than 300 μm in diameter at the -10°C level. The PACE AgI seeding experiment, conducted in Illinois, used and evaluated the Index of Coalescence Activity as one of a number of tools used to forecast cloud characteristics of clouds to help in the recommendation of whether to seed or not seed on a particular day (Czys and Scott 1993).

The presence or absence of coalescence activity is also a major concern for hygroscopic seeding. Because hygroscopic seeding already is being employed at some places in Texas, it is appropriate to develop some guidelines for its use and evaluation. If the cloud tops are warm (i.e., > 0°C), hygroscopic seeding is the only option, if indeed any method is to be employed. If the tops are supercooled and loaded with raindrops, hygroscopic seeding is not the better choice. It makes no sense to seed to enhance coalescence and the formation of raindrops if natural conditions are already producing them in large concentration. Further, model simulations on hygroscopic seeding show no effect from the seeding of highly maritime clouds containing raindrops. It is important, therefore, to predict when the clouds will produce raindrops naturally and to diagnose in real time whether the clouds are producing raindrops naturally.

1.1 The Index Of Coalescence Activity

One way of predicting in advance whether the supercooled portions of clouds on a particular day will contain raindrops is to use the Index of Coalescence Activity (ICA), which was derived and used by Czys (Czys and Scott, 1993; Czys et al., 1996) from the work of Mather et al, (1986). Working in South Africa, Mather et al. (1986) showed that the presence or absence or supercooled drizzle and rain drops (> 300 microns diameter) at a temperature of about -10°C was related to cloud base temperature (CB_T) and the buoyancy at 500 mb (PB), where PB is defined as the temperature difference at 500 mb between the pseudoabiabat that runs through cloud base and the environmental temperature. From their data, Mather et al. (1986) determined a discriminator function, L, between clouds with supercooled drizzle and raindrops and those without, such that:

$$L = b_o + b_1 CB_T + b_2 PB \qquad (1)$$

Where the coefficients b_o, b_1 and b_2 were chosen to maximize differences between drops and no drops when L = 0 (Panofsky and Brier, 1958).

This relationship makes good sense physically because it indicates that coalescence is related to the length of time it takes an air parcel to rise from cloud base to the supercooled portion of the cloud. If CB_T is warm, the distance over which coalescence processes can operate within the parcel before it reaches the −10°C isotherm is large. PB implies an updraft speed. When the PB is large and positive, the air is unstable and the updrafts will be strong. Thus, when CB_T (distance) and PB (speed) are considered together, they represent a duration for coalescence. If the time is short, either because the updraft speed is large, cloud base is cold, or both, the likelihood that the cloud will produce drizzle and raindrops before the cloud top reaches the −10°C level is small. If the time is long for opposite reasons, coalescence will be active in the clouds and raindrops will be detected at the −10°C isotherm. In extreme cases, the time can be so long that coalescence takes place low in the cloud and the drops fallout, never reaching the supercooled portion of the cloud.

With the physics on a sound footing, Czys and Scott (1993) determined that the temperature at the convective condensation level (T_{CCL}) was a reasonable approximation for CB_T and made the appropriate substitution in equation (1). They then solved equation (1) for L = 0, using the plot provided by Mather et al. (1986), to obtain:

$$ICA = 8.6 - T_{CCL} + 1.72PB \qquad (2)$$

With this solution, negative ICA values are indicative of conditions when supercooled drizzle and raindrops are found in the clouds. If the ICA is strongly negative, the raindrop concentrations will be less because many of the drops will already have fallen from the clouds before reaching −10°C. When the ICA is positive, little, if any, supercooled drizzle and raindrops are expected in the clouds.

1.2 The ICA Related To Coalescence In Thailand

In addition to South Africa and Illinois, the ICA also was found to perform well in Thailand as a predictor of in-cloud coalescence activity as shown in Figures 1 and 2. Figure 1 is a scatter-plot from Sukarnjanaset et al. (1998) in which each plotted point represents ICA vs. either the median maximum or the mean maximum droplet or frozen droplet size in the supercooled portions (about-8°C) in Thai clouds. Thailand data are strictly aircraft measurements for both the droplet size and the cloud base temperature (CB_T). The correlation for the mean and median relationship are 0.65 and 0.66, respectively. Best fits to the mean (solid line) and median (dashed line) data are as shown. The results indicate that the droplet sizes increase as ICA decreases. Figure 2 is a scatter plot of visual estimates of in-cloud rainfall vs. ICA. Again it can be seen the in-cloud rain content increases as ICA decreases.

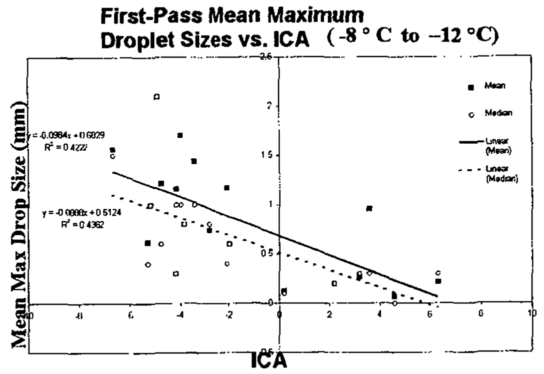

Figure 1. *Scatter-plot of the ICA vs. either the maximum median or mean for a droplet or frozen droplet size in the supercooled portions of Thai clouds (-8 °C). (Diagram is from Sukarnjanaset et al. 1998)*

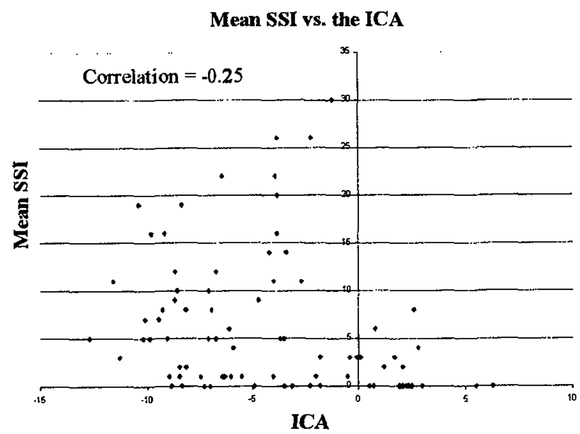

Figure 2. *Scatter-plot between ICA and the mean SSI values for days of experimentation in the Thai cold-cloud seeding experiments from 1993 through 1998. SSI are visual estimates of in-cloud rainfall.*

1.3 The ICA And Coalescence In Texas

The value of the ICA is being investigated in Texas by relating the Index of Coalescence Activity to the height of First-echo Tops (FET). First-echo Tops are used because: 1) first echoes should be indicative of coalescence activity, 2) aircraft data are not readily available, 3) it might afford the opportunity to use readily available radar data, and 4) the operational possibility of using FET as a tool to discern the type of seeding technique. Low First-echo Tops indicate active coalescence and the use of AgI might be appropriate where as high First-echo Tops indicate low coalescence activity and hygroscopic seeding might be a more appropriate method. The Index of Coalescence Activity has been calculated for 33 days during the 1998 season using the Midland and Del Rio soundings and for 34 days using the Corpus Christi soundings. The First-echo Top heights for the same days have been calculated using TITAN software with the San Angelo WTWMA and the Pleasanton STWMA WSR-74c 5-cm radars.

1.3.1 West Texas

The West Texas Weather Modification Association (WTWMA) has had an operational cloud seeding project in West Texas since 1996. The WTWMA consisted of eight full counties and a small portion of one county during the 1996 season. The total seeding coverage area for 1996 was just over 7 million acres. In 1997 the seeding area changed by one county to seven full counties and one partial county for a total of 6.4 million acres (Figure 3). Operations are run from the radar located at Mathis Field in San Angelo.

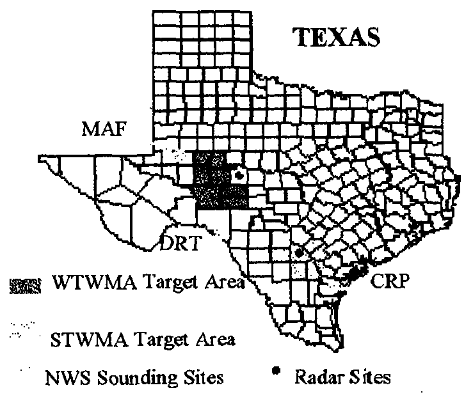

Figure 3. *Map of the WTWMA and STWMA target areas with related radar and NWS sounding sites.*

The climate of the seeding area for the WTWMA can best be described as a combination of both continental and sub-tropical. San Angelo is on the dividing line between the Texas Hill Country and the Edwards Plateau, the start of the West Texas desert. The northern portion of the seeding area is most represented by a continental regime with a sub-tropical regime influencing the southern portion. During the spring and early summer months fronts and/or drylines usually spawn convective activity. During the late summer and early fall seeding events are more likely to have a sub-tropical influence as tropical waves and/or storms from the Gulf of Mexico and Pacific moisture from the sub-tropical jet move through the seeding area.

The 1998 seeding season turned out to be an abnormal year. The spring and early summer had fewer than normal convective events, leaving West Texas with severe drought conditions. Mid summer was dominated by High pressure located over the center of Texas, making the general flow for West Texas southeasterly. By mid-August to mid-September a few tropical systems briefly helped to alleviate the southern section of the target area from severe drought conditions. Seeding operations were suspended on a number of these tropical events due to flooding potential. This tropical moisture stayed mainly south and east of San Angelo.

1.3.2 South Texas

The South Texas Weather Modification Association (STWMA) has been running a cloud seeding project in South Central Texas since 1997. During the 1997 and 1998 seasons, the South Texas project performed seeding missions over seven counties south of San Antonio. The project's WSR-74c radar is located in Pleasanton at the Municipal airport, where the seeding operations are run (See figure 3 in section 1.2.1).

The climate of the seeding area can best be described as sub-tropical with a modest continental influence. A southeast flow, common during the spring and summer months, brings in warm, moist air from the Gulf of Mexico. This is seen in the fact that dew points during the summer average in the mid-70's and occasionally approach 80 degrees. The sea breeze, especially prevalent in the area during the summer, is often a catalyst for shower and thunderstorm development, although other features can and do contribute to convective activity.

The 1998 season was not an average year for South Texas. Much of the spring and summer experienced severe drought conditions, and it was not until August when the weather finally became more active and the seeding opportunities increased. In fact, from August through mid-September, an MCS, two tropical storms, and a couple of tropical waves affected the area, resulting in self-imposed suspensions over a number of days because of the potential of flooding.

2. METHODOLOGY

Echo tops were chosen because they indicate the maximum elevation at which raindrops are present within the cloud. Also, echo tops are convenient to use and readily available making it easier to transition from a research to an operational cloud seeding program. On days when seeding occurred, the respective radar was closely monitored for first echoes forming within a 100 km radius of that radar. A radius of 100 km was used in order to include First-echo Tops that were at the 2 km level and above. The top of the 'first echo' was found by taking a cross-section through it and simply noting the height of the top of the echo. This is a convenient feature of the TITAN radar display software. For the days that the first-echoes met the above requirement, First-echo Tops were determined and the average was calculated. This average value was used as the First-echo Top for that particular day.

For the 1998 seeding season, the Index of Coalescence Activity was calculated for each day that seeding operations took place based on the 12:00 UTC sounding. Days on which the Index of Coalescence Activity could not be derived due to a) either bad or non-existing sounding data or b) when the T_{CCL} was above the 500 mb level were eliminated.

2.2 Sectoring The Radar In West Texas

Two NWS sounding stations are close to the WTWMA's rain enhancement program target area. They are Midland (MAF) and Del Rio (DRT). The 12 UTC morning sounding was used to determine the Index of Coalescence Activity for each station. The San Angelo radar was partitioned into two sectors; one toward each of the sounding locations in order to help distinguish between the continental and sub-tropical air masses. The MAF sector was defined as the 232-degree radial, from the WTWMA's San Angelo radar, to the 360-degree radial. The DRT sector was from the 112-degree radial to the 232-degree radial. First-echo Tops that were not observed within the 100 km radius, within the appropriate sector radials, or didn't form within the particular sector, were eliminated from the study.

2.3 No Sectoring Needed In South Texas

For South Texas, the morning sounding at Corpus Christi (CRP) was used to calculate ICA. Unlike San Angelo, the sounding from CRP was the only one used because it is to the Southeast of the target area, and as mentioned earlier, a southeast flow is predominant over the target area during a majority of the seeding season.

3. RESULTS

The Index of Coalescence Activity conceptually verifies with South Texas (CRP) having mostly negative ICA values, showing a tropical influence and West Texas (MAF) ICA values mostly positive showing a continental influence. The Index of Coalescence Activity values derived from the Del Rio sounding show, with little surprise considering it's location, the combined influence of both sub-tropical and continental air masses with a more even distribution of both positive and negative values.

3.1 Results For West Texas

Scatter plots between the index of Coalescence Activity (the abscissa) and the First-echo Tops (ordinate) have been constructed for Midland and Del Rio NWS soundings as shown in Figures 4 and 5 respectively, along with the linear correlation coefficients and best fit lines. The average ICA values for MAF and DRT were 4.3 and 1.35 respectively. The Midland ICA values show 28 positive to 5 negative out of 33 total values. Del Rio ICA values are 20 positive to 13 negative out of 33, suggesting that the southern portion of the WTWMA seeding area has the opportunity to utilize either AgI or hygroscopic or a combination of both. In the northern portion, hygroscopic seeding may be a useful method/mechanism for producing raindrops. But these MAF ICA values do not seem to be representative of or relate to the average First-echo Top for the 1998-seeding season. The average FET for the MAF sector is 6.7 km, which would seem to be a little low for what one would expect from a 4.3 average ICA value. The correlation between ICA and FET is 0.38 for the MAF sector confirming that the MAF derived ICA values do not represent the observed First-echo Tops well.

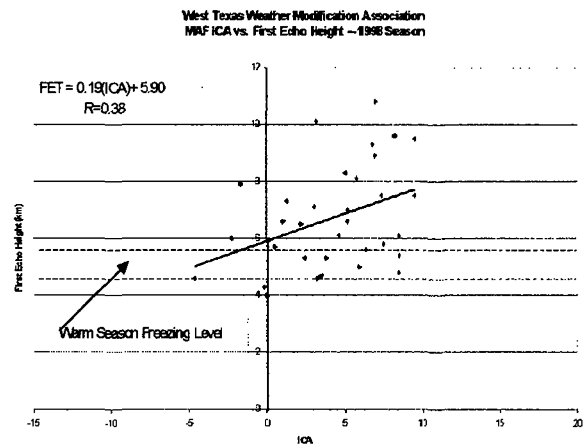

Figure 4. *Scatter-plot of ICA vs. FET for 33 seeded days in the 1998 season. The ICA is derived from the MAF 12 UTC sounding. The average FET is calculated using a cross-section from the WTWMA radar.*

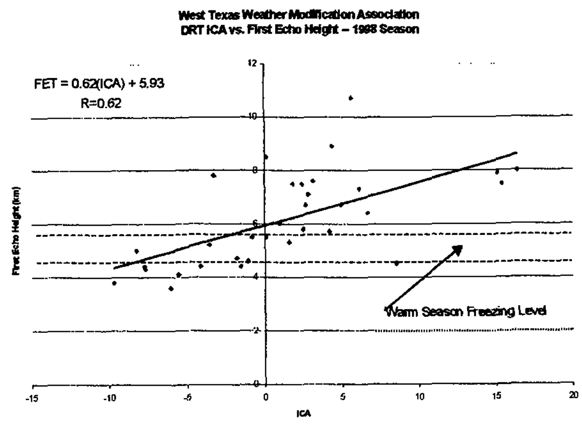

Figure 5. *Scatter-plot of ICA vs. FET for 33 days in the 1998 season. The ICA is derived from the DRT 12 UTC sounding. The average FET is calculated using a cross-section from the WTWMA radar.*

First-echo Tops and ICA values relate better for the DRT sector with average FET of 6.2 km. Note there is a positive correlation, 0.62, between ICA and the First-echo Tops. This means as ICA decreases the First-echo Tops decrease. For large negative ICA values the tops of the first echoes are less than 5 km in most instances, meaning the echoing portion of the cloud containing the raindrops is warmer than 0°C. It would be important to note at this point that the average freezing level in Texas runs between 4.5 and 5.5 km AGL. It is questionable whether hygroscopic seeding would enhance the rainfall from such clouds.

3.2 Results For South Texas

Figure 6 shows a scatter plot between ICA values (the abscissa) and the First-echo Tops (ordinate) that was constructed for the Corpus Christi NWS sounding, including the linear correlation coefficient and best fit line. It comes as no surprise that the vast majority of days in the South Texas project saw ICA values less than zero. The average ICA during the seeding period was -3.7 with 28 negative values and 6 positive values out of 34 total (two days have the same values). This would suggest that the clouds were naturally producing raindrops effectively, and that hygroscopic seeding would likely not produce a significant enhancement in the rainfall. To further support this, the average first-echo height during the 1998 season was 5.83 km AGL with a correlation between ICA and the FET of 0.51. Since the average warm season freezing level in South Texas runs between 4.5 and 5.5 km AGL, most of the cloud is warm, and most certainly contains raindrops.

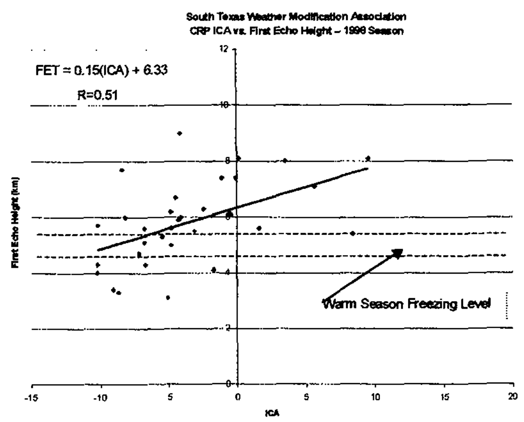

Figure 6. *Scatter-plot of ICA vs. FET for 34 seeded days in the 1998 season. The ICA is derived from the CRP 12 UTC sounding. The average FET is calculated using a cross-section from the STWMA radar.*

4. DISCUSSION

Because the behavior of FET is consistent with the hypothesis of increased coalescence activity with increasingly negative ICA, it should be possible to use the Index of Coalescence Activity to determine which type of seeding should be employed. We can surmise that when ICA is large and negative silver iodide seeding should be employed instead of hygroscopic seeding if seeding is to be done. As ICA increases, however, coalescence activity is weak at best and hygroscopic seeding should take precedence over silver iodide seeding. Regardless of which method is chosen at the outset, the decision should be checked using the First-echo Tops and perhaps checked again using in-could measurements of a candidate cloud. Whenever the First-echo Tops are low relative to the height of the 0°C isotherm, hygroscopic seeding is probably not the better choice regardless of the ICA. Silver iodide should be used in those circumstances assuming cloud heights rise above the –5°C level.

4.1 First-echo Tops And Hygroscopic Seeding Evaluation

A physical means of evaluating hygroscopic seeding is embodied in Figures 4, 5 and 6 in which First-echo Tops are plotted vs. ICA. If operational seeding is conducted on days when ICA is large and positive, the natural cloud First-echo Tops will be high and supercooled. By identifying a seeding area of effect on such days, one might look at the tops of the First-echo Tops in the presumed area of effect to determine whether they have been lowered in this area as a result of seeding. If no lowering is evident over the course of a number of seeding events, one would have reason to question the effectiveness of the hygroscopic seeding. On the other hand, if hygroscopic seeding is effective, the mean First-echo Tops as a function of ICA should be less than for clouds that did not ingest the hygroscopic material. This analysis will be pursued in the Texas evaluation effort.

4.2 The MAF Sector Correlation

During this study the events that had positive Index of Coalescence Activity values and lower FET than expected (according to the trend line) were looked at on an individual basis. Concerning the low correlation for the MAF sector three possible reasons were looked into. The first is that the air mass at the sounding station location was not representative of the air mass where and when the First-echo Tops were measured. The second reason is the First-echo Tops lowered as the new cells ingested water droplets from the older cells next to them. Thirdly, the temperature at the CCL (T_{CCL}) may not be a good representation of the actual cloud base temperature (CB_T).

The difference in air masses between Midland and San Angelo may have played a significant role in why the Index of Coalescence Activity had a difficult time predicting the FET and why the MAF correlation did not turn out well. Looking at the individual cases where the expected FET derived from the ICA value deviated greatly from the actual FET, it was found that there was a difference in the air mass between Midland and San Angelo. This was in the form of either a dryline/front or tropical system from the Gulf with San Angelo being in the warm and moist air mass.

In the spring there is a movement of moist air from east to west overnight and then a return back to the east during the daytime hours. By the time the afternoon thunderstorms develop and the First-echo Tops are measured the dryline has moved east. Also, on many days the dryline or front stalls between Midland and San Angelo where the moisture laden air will give lower FET than the Index of Coalescence Activity will predict in the dryer air of Midland. When the positive ICA values were greater than three (ICA > 3) and First-echo Tops were below 6 km, every case showed a difference in the air mass between Midland and San Angelo. The events in the spring and early summer mainly are due to a dryline or a front lying between Midland and San Angelo. (Sub-tropical events will be discussed later.) The dry air in Midland will give positive derived ICA values and therefore predicted high First-echo Tops. But the clouds would form in the moisture-laden air east and southeast of Midland returning lower actual First-echo Tops. In the relationship where the ICA values were greater than 5 but less than 10 and the FET were very large in height, over 9.0 km, a change was found in the air mass from the 12 UTC sounding to the time that FET started to occur. For example, a dryline progresses west to east during the day. The cells then develop in the dryer region of the air mass. This explains why the predicted FET were lower than the observed FET.

The late summer and early fall of 1998 had a number of tropical systems move into Texas bringing a tropical air mass to the target area. The tropical air mass stayed in the southern and eastern parts of the target area pushing into the MAF radar sector yet not all the way to Midland where the sounding is taken. This would account for getting low First-echo Tops for the MAF sector compared to higher ICA values and would in turn help explain the discrepancy between the two values and why the correlation between the two was low.

With respect to the second reason, a review of each of the cases for the MAF sector First-echo Tops showed the possibility that a few days could have been effected by ingesting water droplets from surrounding mature cells. By ingesting the water drops the new growth's first echoes would start lower in height. This effect can be seen more readily when cells are clustered. There were a couple of the large positive ICA and low first-echo height days in which the 'cluster effect' could be a possible cause of the low First-echo

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Tops. The 'cluster effect' may also explain the few events in South Texas when the CRP derived ICA predicted higher values than the actual First-echo Tops. More comprehensive analysis of this feature is being done on the 1998 season data and will be done in future years.

The radar was sectored to alleviate the differences between continental and sub-tropical air masses but it did not substantially reduce the differences for the 1998 season. Del Rio ICA values better represented the environment in the WTWMA seeding area for the 1998 season. When sectoring was eliminated, The DRT correlation between ICA and FET nominally increased to 0.64. As expected Midland's correlation remained low (< 0.40).

The third case concerning the low correlation for the MAF sector is that the T_{CCL} is not a perfect indicator of the CB_T. Due to the small 1998 data set of aircraft measurements preliminary analysis comparing the T_{CCL} with the CB_T is inconclusive. Further investigation is needed in this area.

5. CONCLUSIONS

Two types of air masses, continental and sub-tropical, affect the WTWMA target area. The data shows that the line between these two air masses tends to oscillate between Midland and San Angelo. The Index of Coalescence Activity vs. FET values for the MAF sector shows this to be true. This makes the forecast of First-echo Tops using the Index of Coalescence Activity derived from the MAF sounding less than straightforward. The overall weather pattern should always be considered, but special consideration should be taken were the dryline/front is positioned, or the influence of a tropical system from the Gulf of Mexico can significantly affect differences in the MAF ICA value vs. the FET.

The Index of Coalescence Activity derived from the DRT sounding proved to be a better representation of the air mass in the 112 to 232 radial sector as well as the seeding area as a whole with a correlation of 0.62 and 0.64 respectively. Although at times it can be seen that there is some variation in the ICA value and the FET for the 1998 season, the Index of Coalescence Activity derived from the DRT sounding looks to be a good indicator of coalescence at the -10°C level (i.e. the seeding level).

The Corpus Christi ICA values and the low First-echo Tops conceptually relate to the sub-tropical conditions that one would expect around the Gulf of Mexico. The Index of Coalescence Activity did an adequate job in predicting the FET considering that the radar sits over 175 km from the coast while the sounding station is on the coast, and a modest continental air mass can affect the seeding area without influencing the sounding station.

The number of positive vs. negative ICA values for each of the three stations shows that there may be good reason to have both cold-cloud and hygroscopic seeding methods available in Texas. This is especially true for a region that is influenced equally by both continental and maritime air masses.

A detailed study of the radar data for the 1998 season is in progress. Until this is complete, it remains unclear whether or not the Index of Coalescence Activity is a good predictor of seeding type for the Texas projects. However, there is enough positive evidence to advocate more research in regard to the use of the ICA vs. FET for evaluation purposes as well as an operational forecasting tool in Texas seeding projects. Further research is and will be designed to include: 1) the study of how representative the morning soundings are to the actual afternoon conditions, 2) how the 'cluster effect' relates to FET, 3) analysis of T_{CCL} to CB_T, 4) testing Mather's discriminator function at the -10°C level in Texas, and 5) a variation of the research done by Czys et al. (1996) involving a climatelogical analysis of the ICA in Texas. The study of the Index of Coalescence Activity with relation to First-echo Tops will thus continue in Texas.

6. ACKNOWLEDGEMENTS

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