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OBJECTIVE FORECASTING OF SOME INDIVIDUAL CLOUD CHARACTERISTICS IN THE 1989 ILLINOIS CLOUD SEEDING EXPERIMENT

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ABSTRACT. A simple objective procedure used exploratively to forecast the occurrence, height, and coalescence activity of summertime convective clouds in Illinois during the cloud seeding trials of the 1989 Precipitation Augmentation for Crops Experiment is described. The method used the temperature of the convective condensation level (T_{CCL}) and potential buoyancy (PB) at 500 mb, easily determined from morning National Weather Service sounding data, to forecast afternoon convection. Categories of maximum echo top heights were found to arrange according to T_{CCL} and PB. The physical basis of T_{CCL} and PB to implicitly represent a period of time for coalescence to produce supercooled drizzle and rain drops is discussed. The technique performed well at forecasting the occurrence and height of afternoon convective clouds, and the accuracy of the occurrence forecast improved if precipitable water was used as an additional criteria. Aircraft measurements of supercooled rain drop concentrations showed that a discriminator function, dependent only on T_{CCL} and PB, gave a good indication of the presence or absence of supercooled drizzle and rain drops in the updrafts of clouds at the -10°C seeding level. Median concentrations of supercooled drizzle and rain drops ($N_{D>300}$) in updraft regions at the -10°C level were found to be best approximated by a third order polynomial dependent on T_{CCL} and PB, presenting a possible physical link between cloud scale environment and in-cloud conditions.

1. INTRODUCTION

An objective convective cloud forecasting method was developed and tested as part of the 1989 Precipitation Augmentation for Crops Experiment (PACE). The forecasting method is somewhat unique in that forecasts of some specific cloud characteristics, such as maximum echo height and coalescence activity, can be obtained which are not normal parts of the National Weather Service (NWS) forecast products. Two thermodynamic parameters, the temperature of the convective condensation level (T_{CCL}) and potential buoyancy (PB), which can be easily determined from NWS morning sounding data were the primary input for the forecasting procedure. The procedure produced a forecast of convective occurrence (in the form of an operational recommendation of Go, Stand By or No Go), a forecast of probable maximum radar echo height, and an indication of the presence or absence of supercooled drizzle and rain drops at the -10°C level in clouds, a physical requirement of the dynamic seeding hypothesis, which was under investigation in the 1989 experiment (Changnon et al. 1991).

2. BACKGROUND

During the late fall of 1946, the first modern cloud seeding experiment was carried out east of Schenectady, New York where small fragments of dry ice were dispersed into the top of a supercooled stratus cloud (Schaefer 1946). Since then hundreds of cloud seeding projects, ranging from well planned commercial operations to carefully designed scientific experiments, have been conducted for precipitation enhancement (Todd and Howell 1985). Virtually all of these activities have depended on strong forecasting efforts. Thus, only a few have been selected for review to provide a practical context for the present work.

Forecasting operations in previous modern summertime cloud seeding experiments have had at least two important purposes. The first has been to provide an indication of whether meteorological conditions (clouds) suitable for experimentation may develop. For this purpose, forecasting procedures have usually followed one or more "subjective" steps, in which the forecaster, guided by scientific principles, differently interpreted and weighed the importance of the meteorological data available from day-to-day. The second important function of forecasting operations in cloud seeding experiments has been to provide a means to "objectively" classify (and/or select) events according to meteorological (and/or cloud) similarity, thereby permitting the use of statistical methods to help assess seeding effects. Typically, in the "objective" process, a predetermined set of rules was consistently followed to arrive at a forecast, or more commonly a diagnosis, of the weather conditions for experimentation.

Almost all modern summertime cloud seeding experiments have had subjective and objective components in their forecasting operations. For example, the Australian Isolated Cumulus Experiment, conducted during 1962-65, relied on subjective practices to forecast the development of isolated cumulus (Bethwaite et al. 1966). The selection of individual clouds for seeding was determined by personnel in the seeding aircraft using criteria such as, general cloud appearance, longevity of cloud existence, and extent of isolation from other clouds. Subjective forecasting practices were also applied in seeding experiments conducted over Tasmania from 1964-70 (Smith et al. 1977). In these experiments on rainfall increase from stratiform and cumuliform clouds, subjective forecasting provided guidance on the probable development of clouds, while the acceptability of a cloud to receive treatment was based on the detection of supercooled cloud water, and on visual criteria, such as, horizontal cloud spacing and vertical cloud tilt.

The Israeli I and II experiments, conducted from 1961-67 and from 1969-75 (Wurtele 1971; Gagin and Neumann 1981), used subjective techniques to forecast the occurrence of clouds suitable for experimentation. However, rather than classify by meteorological similarity, a randomized schedule for release of the type of seeding material was used. Treatments were delivered if cloud tops were colder than -5°C, and if cloud bases were less than 2 km (AGL).

Research on hail suppression over northeastern Colorado during the National Hail Research Experiment (NHRE) also relied on subjective forecasting techniques to alert for the possibility of hail-producing weather (Crow et al. 1976). However, selection of clouds for study was based on whether echoes with reflectivities greater than 45 dBZ were detected by a 5 cm wavelength radar.

Project Whitetop was designed to objectively classify days by meteorological similarity to facilitate the use of statistical evaluation for seeding effects (Braham 1966). In Whitetop, conducted over south central Missouri during the summers of 1960-64, the clouds which developed during any particular day were considered to be similar if the precipitable water amounts were 33 mm and 27 mm, calculated from the 0700 LST soundings at Little Rock, Arkansas and Columbia, Missouri, respectively, and if the low-level wind direction over the approximate center of the research area was between 170° and 340°.

Another example of a cloud seeding experiment which made use of subjective forecasting, as well as objective classification of similar days by diagnosis of the meteorological conditions, was the Rapid Project (Dennis and Koscielski 1969). In this experiment on rain increase and hail suppression conducted in western South Dakota during the summer months of 1966-68, an objective procedure was used to categorize days into one of four types according to what might be considered progressively favorable conditions for convective precipitation. These conditions were based on precipitable water, low level winds, and vorticity advection.

The North Dakota Pilot Project (NDPP) was conducted during the summers of 1969-72 (Dennis et al. 1975), and used procedures to objectively type days that were very similar to those used in the Rapid Project. However, to facilitate statistical evaluation in the NDPP, and yet appease the desire of local citizenry who wanted seeding of all opportunities, a data blocking procedure was incorporated into the design such that 75% of all days were pre-selected as seedable. In the experiment, the selection of individual days for treatment was subjectively determined, and a prediction of cloud suitability was not made.

Forecasting operations for cloud seeding experiments advanced with the development of computer cloud models which could indicate cumulus growth under natural and seeded assumptions. One of the first uses of computer cloud models in weather modification experiments occurred in the cloud seeding studies of Caribbean clouds (Simpson et al. 1965). The model used in these studies was improved and used in cloud seeding studies over southern Florida in 1968 (Simpson and Wiggert 1969), and in the Florida Area Cumulus Experiment (Simpson and Wiggert 1971).

The Florida Area Cumulus Experiment (FACE) made extensive use of 1-D cloud model results. FACE was a randomized seeding experiment designed to study the possible promotion of larger and better-organized cumulus cloud systems through buoyancy enhancement from glaciogenic seeding (Woodley and Sax 1976). In the forecasting operations of FACE, rawinsonde data from the 0600 LST sounding at Miami was used as input to the 1-D model to calculate maximum cloud seedability (the difference between calculated maximum heights of natural versus seeded clouds) for a range of cloud radii. Output from the model was combined with 10-cm radar data to provide a daily seeding suitability factor, defined as the difference (S-Ne) between the calculated enhancement of cloud growth (S), and the number of hours (Ne) during which precipitation echoes were observed within the target for the inclusive period from 1000 to 1200 LST.

The threshold value of the seeding suitability factor was set to be biased toward days with a large seeding potential, and away from days with persistent late morning precipitation (Woodley and Williamson 1970). If S-Ne was less than a threshold of 1.5, then operations were terminated for the day. If S-Ne was greater than the threshold, then the research aircraft was launched to investigate the suitability of individual clouds in the target. Clouds were deemed to be similar on the basis of showing "a hard cauliflower appearance", and "a favorable prognosis for continued growth." External and internal properties such as, cloud top temperature, supercooled liquid water content, and updraft strength were also employed. If cloud properties did not meet these criteria, then the aircraft was required to return to base, and operations were terminated for the day. If the criteria were met or exceeded, a "Go" day was declared and seeding commenced.

A 1-D cloud model was also crucial in the forecasting procedures of Project Cloud Catcher conducted in the northern Great Plains during the summers of 1969-72 (Koscielski and Dennis 1972). This experiment tested the effectiveness of salt (NaCl) and silver iodide (AgI) as seeding agents to initiate or enhance precipitation, respectively. A 1-D model (Hirsch 1971) was used to calculate the maximum cloud top height of natural and seeded clouds for 5 different updraft radii. Model results were used to select the type of seeding agent to be used for an operation based on the rationale that 1) on days with clouds characterized by strong calculated updrafts, precipitation could be initiated by NaCl seeding to stimulate coalescence processes, and 2) on days with clouds characterized by weak calculated updrafts, precipitation could be augmented by AgI seeding to enhance cloud vigor.

Computerized meteorological instrumentation for airplanes had progressed sufficiently by the time of the High Plains Cooperative Project (HIPLEX) to allow for a major departure from objectively classifying days on the basis of meteorological conditions, and calculated and visual cloud properties, to classifying and selecting clouds for study on the basis of detailed objective computer analysis of in-cloud conditions (Dennis et al. 1984). HIPLEX was a randomized seeding experiment to study precipitation initiation in semi-isolated cumulus congestus clouds. In HIPLEX, conducted over the High Plains of Texas, Kansas, and Montana during the summers of 1975 to 1980, missions were launched based on subjective forecasting criteria, but seeding occurred only after a candidate cloud exhibited either one of two predefined types (Type I and II) of in-cloud and external conditions. All clouds were required to possess similarity in supercooled water contents, ice crystal concentrations, diameters, absence of precipitation detectable by the aircraft weather avoidance radar, cloud base temperature, and spatial separations. Type I clouds were distinguished from Type II by cloud top temperature, and updraft velocity.

Forecasting has been an important component of PACE since its inception. In the 1986 PACE field experiment, the potential use of "blocking" according to synoptic weather type was explored (Changnon et al. 1987). This method was found to be unsatisfactory because it produced too few events in each synoptic category of 1) cold front, 2) warm-front, 3) stationary front, 4) low pressure, 5) squall zone, and 6) air mass. Thus, many summers of experimentation would be required before an acceptably large sample size in each category could be obtained.

Consequently, research refocused on development of methods to forecast specific cloud characteristics which were closely related to requirements set by the seeding hypothesis under investigation; in this case, the dynamic seeding hypothesis for Illinois (Ackerman and Westcott 1986; Simpson and Woodley 1971). The primary objective of dynamic seeding is to invigorate cloud vertical motion by rapid release of latent heat from freezing of all or most of the available supercooled water. This release of latent heat is supposed to increase upper level cloud buoyancy, and thereby promote cloud growth and merger. Such clouds are supposed to grow larger, last longer, or both, to process more water vapor, and produce more rain. In dynamic seeding, seeding material is delivered near cloud top at the -10°C level to effect the lower cloud volume in order to freeze the supercooled water earlier than if natural glaciation processes operated alone. Ejectable flares have been most frequently used in dynamic seeding operations to best deliver seeding material to updraft regions.

The dynamic seeding rationale immediately imposes at least three basic requirements for operational forecasting. First, an occurrence forecast must be made so that staff and facilities can be prepared for experimentation. Secondly, maximum cloud top (echo) heights must be forecasted since clouds must reach at least the -10°C level (approximately 20,000 ft in Illinois in summer) in order to possess a region of supercooled water. Lastly, it is desirable to have advanced knowledge about the clouds microstructure, in particular whether supercooled drizzle and rain drops ($D > 300$ μm) will be present at the seeding level, because large latent heat releases can be realized from these conditions. Hence, the procedure developed and tested in the 1989 PACE field program aimed at satisfying these basic requirements.

3. METHOD FORMULATION AND APPLICATION

Figure 1 shows the geographic region over which operations were conducted in the 1989 PACE field experiment, and the target area, defined by a 190 km (approximately 100 nm) radius circle centered on Champaign (CMI), Illinois. In analysis of the 1986 PACE forecasting operations, 5 stability indices were found to be strongly associated with the occurrence of convection in the PACE target area (Scott and Huff 1987). Scott and Huff defined a convective day as any day with at least one maximum echo top within the target area greater than 6.7 km (22,000 ft) anytime during the operational period from 1600 to 0100 UT (1100 to 2000 LST). A non-convective day was defined as any day with all maximum echo tops less than 6.7 km, including days with no echoes. These definitions were later changed for evaluation of the objective forecasting method used in the 1989 PACE experiment. Maximum echo tops were extracted from the NWS hourly radar summaries for the WSR-57 radars located at Marseilles, Illinois; St. Louis, Missouri; and Evansville, Indiana. These sites provided full coverage of the PACE target area. One of the interesting findings from the work of Scott and Huff was that the *morning* sounding at either Peoria (PIA) or Salem (SLO), Illinois gave a reasonably good indication of the occurrence of *afternoon* convective activity, which has been found to be not true for other geographic regions such as the front range of Colorado (Wilson and Mueller 1991), but was true for HIPLEX in eastern Montana (Hartzell and Jameson 1981). Furthermore, convective days could be proficiently detected if the stability indices for PIA and SLO both exceeded an empirically determined threshold value.

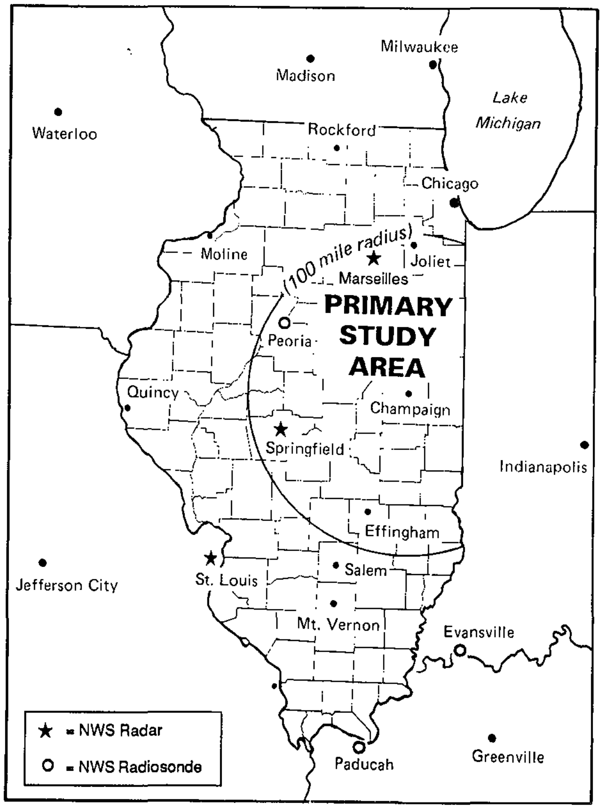

Figure 1. Study area for the 1989 PACE field experiment.

The objective forecasting procedure used in the 1989 PACE field experiment was also developed from the finding that the amount of coalescence activity in the convective clouds of Eastern Transvaal was strongly linked to thermodynamic conditions (Mather et al. 1986). From analysis of 3 years of microphysical measurements that Mather et al. had, 2D images of drops greater than 300 μm diameter were found at the -10°C level in 40% of 42 storms measured. Furthermore, the presence of supercooled drizzle and rain drops at the -10°C (seeding) level was strongly related to cloud base temperatures (CB_T) and buoyancies. Mather et al. defined a parameter called potential buoyancy (PB) as the difference at 500 mb between the pseudoadiabat that runs through cloud base and the environment temperature. Potential buoyancy and Lifted Index are similar to one another except that Lifted Index is computed as the temperature difference at 500 mb between the environment temperature and the pseudoadiabat that runs through the forecasted cloud base. Hence, Lifted Index and Potential Buoyancy have opposite signs and differ somewhat in magnitude.

Figure 2, reproduced from Mather et al., shows the separation between storms that had clouds with large (D > 300 μm) drops at the -10°C level, and storms that had clouds which did not, according to CB_T and PB. In Fig. 2, open circles represent cases where the 2D imagery from a mission showed images of large drops, and x's indicate missions during which large drops were not encountered. From this data, a discriminator function, L, was determined to be

$$L = b_0 + b_1 CB_T + b_2 \Delta T_{500} \qquad (1)$$

where the coefficients b_0, b_1 and b_2 were chosen to maximize differences between drops and no drops when $L = 0$ (Panofsky and Brier 1958). Even allowing for the possibility that some of the large, smooth images that were interpreted to be liquid drops when they may have been recently frozen, the discriminator line in Fig. 2 provides a clear indication that the presence or absence of supercooled drizzle and rain drops at the -10°C level is related to cloud base temperature and potential buoyancy.

The distinct separation between days with clouds that develop supercooled drizzle and raindrops and those that do not, is physically related to the length of time for coalescence to operate, implicit in the CB_T, PB parameter space. Cloud base temperature represents a depth between the cloud base and the 0°C isotherm. As cloud base becomes warmer, this depth increases, and thus, a greater distance exists over which coalescence processes can operate within a raising air parcel, assuming that all other factors are equal. Potential buoyancy, unadjusted for the lessening effects of entrainment and condensate loading, implies an updraft velocity, and thus, constitutes a measure of the potential vertical velocity with which a cloudy air parcel may rise. Thus, when cloud base temperature (distance) and potential buoyancy (velocity) are taken in combination, they represent a time or duration for coalescence to operate. If this time is short, either because the updraft velocity is large, or cloud base is cold, or both, the likelihood that the cloud will produce drizzle and rain drops before cloud top reaches the 0°C level is small. Conversely, this time may be too long. Hence, drizzle and rain drops will be produced when updraft velocity and depth between cloud base and 0°C combine to result in an optimal time for coalescence to operate.

Since the parameter space of Fig. 2 apparently represents physical variables related to the production of rain by coalescence, data on the presence and absence of

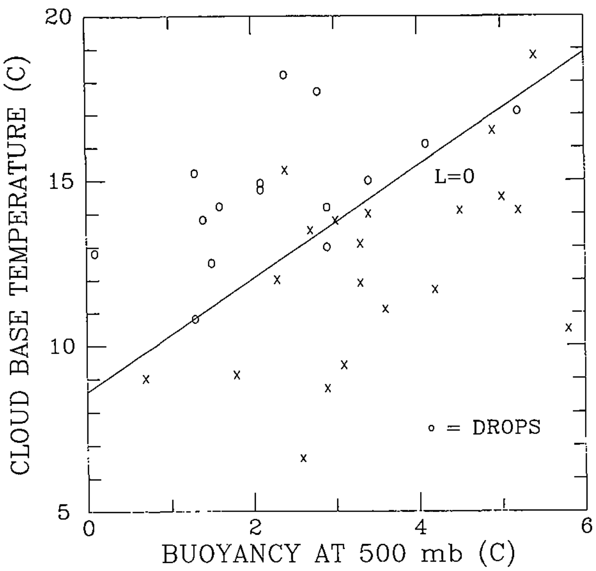

Figure 2. Plot of the presence (o's) or absence (x's) of supercooled drops with diameter greater than 300 μm at the -10°C level according to cloud base temperature and potential buoyancy at 500 mb for storms studied in the Eastern Transvaal (from Mather et al. 1986).

drizzle and rain drops should separate according to CB_T and PB, regardless of geographic location. Results shown in Fig. 2 for Eastern Transvaal should have application to Illinois particularly since the distribution of cloud based temperatures for Illinois (Johnson 1982) is similar to those for South Africa (Mather et al. 1986). Summer convective clouds in Illinois should have supercooled rain drops present at -10°C on days when CB_T and PB intersect above $L = 0$ in Fig. 2, and should be absent on days when CB_T and PB intersect below $L = 0$.

3.1 FORECASTING CONVECTIVE OCCURRENCE

In the development of our forecasting technique, use of CB_T was abandoned in favor of the temperature of the convective condensation level (T_{CCL}) since our experience indicated that this parameter is well correlated to CB_T, and because it is easily obtained from the NWS morning sounding. We next determine if maximum echo top heights were grouped in the T_{CCL}, PB domain, since echo height should be physically correlated with buoyancy, represented by potential buoyancy. Figure 3 is a scatter plot of daily maximum echo heights over the PACE target area versus T_{CCL} and PB for June, July and August of 1986 and 1987. T_{CCL} and PB were calculated for each day on which both mandatory and significant level rawinsonde data were reported to a height of at least 500 mb in the 0700 LST soundings at PIA and SLO. The convective condensation level (CCL) was computed as the intersection of the temperature trace with the average saturation mixing ratio over the lowest 100 mb. Potential buoyancy was defined as the difference between the 500 mb ambient temperature, and the temperature obtained by a moist adiabatic ascent from the CCL to 500 mb.

Each number in Fig. 3 represents a category of height range for the tallest NWS radar echo observed in the target between 1100 and 2000 LST determined from either the Marseilles, St. Louis or Evansville NWS radars. In the event that the same maximum echo top was reported by two or more of the NWS radar stations, the height of the maximum top was taken from the nearest of the NWS radars. Four height categories (0 through 3) are plotted in Fig. 3: a "0" indicates days with no echoes, a "1" indicates days with maximum echo tops ≤ 7.3 km (24,000 ft), a "2" indicates days with maximum tops between 7.3 km and 11.0 km (36,000 ft) exclusively, and a "3" indicates days with maximum echo tops ≥ 11.0 km. These distinctions between short, medium and tall clouds (categories 1 through 3), developed strictly for the objective forecast procedure, were defined on the basis of rural HiCu data collected during Project METROMEX (Braham and Wilson 1978). The distribution of rural HiCu data from METROMEX is bi-modal with one peak in maximum radar echo tops at about 6.4 km (21,000 ft) and another near 12.2 km (40,000 ft), with a minimum in echo heights at 9.8 km (32,000 ft). Our medium-sized echoes were defined roughly by the midpoints between the maximum and minimum height frequencies in the bi-modal HiCu distribution.

Figure 3 shows a definite clustering of tall echoes for values of T_{CCL} in the range of 9 to about 22°C and for

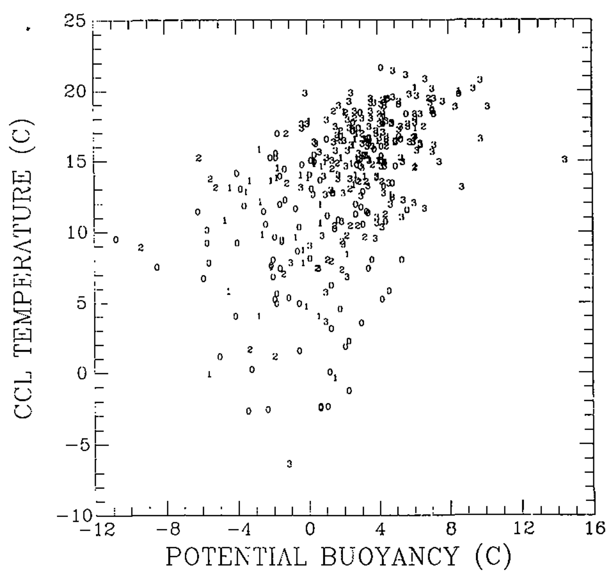

Figure 3. Plot of maximum echo top height category according to PB and T_{CCL}. A "0" indicates days with no echoes, a "1" indicates days with maximum echo tops ≤ 7.3 km (24,000 ft), a "2" indicates days with maximum tops between 7.6 km (25,000 ft) and 10.7 km (35,000 ft), and a "3" indicates days with maximum echo tops ≥ 11.0 km (36,000 ft).

values of PB in the range of -1 to 12°C. Medium-height (category 2) maximum echo tops are slightly less congregated than category 3 echo tops, but still distinguishably cluster over values of T_{CCL} in the range of 1 to 17°C and values of PB in the range -5 to 3°C. Echoes with the short maximum tops (category 1) are even less grouped than the medium-sized echoes, but show some clustering over values of T_{CCL} in the range 0 to 10°C and PB in the range of -4 to 2°C. Days having no echoes are more or less evenly scattered over the T_{CCL}, PB domain, owing to the lack of kinematic representation in Fig. 3.

The clustering visually identified in Fig. 3 was schematically represented and used to objectively make forecasts of Go, Stand By, and No Go days (see Fig. 4). In Fig. 4, Go days, as defined for this objective forecast procedure using the rural HiCu data, correspond to days with mostly category 3 maximum echo tops and is delineated by the horizontal stripping. Stand By days were defined as days having mostly either category 2 or 3 echoes and are delineated by vertical stripping. Thus, if a day had values of T_{CCL} and PB which fell in this region the day was objectively forecast to be a Stand By day. Finally, a No-Go day was defined with mostly either category 0 or 1 echoes, and corresponds to the unstriped region of Fig. 4. Thus, if a day had values of T_{CCL} and PB which fell in the unstriped area the day was objectively forecast to be No Go.

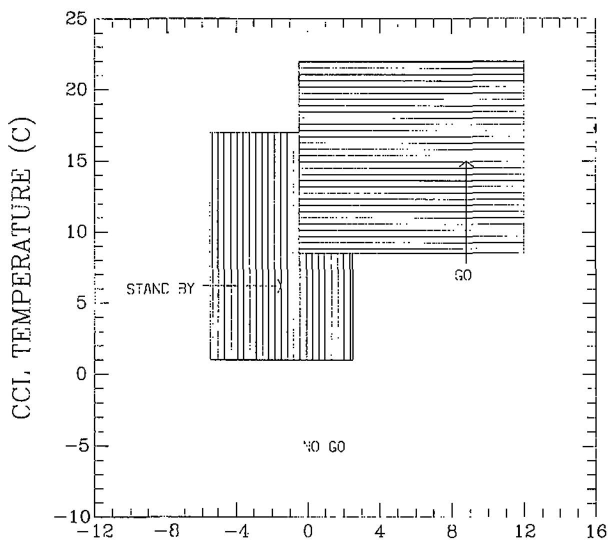

Figure 4. Diagram used to forecast Go, Stand By, and No Go days.

3.2 <u>FORECASTING MAXIMUM ECHO TOP HEIGHT</u>

The organization of maximum daily echo tops shown in Fig. 3 was quantified by computing the frequency of occurrence of each category at each grid point in the domain. Scatter of the maximum echo top heights was discretized using a Cartesian grid with 1°C resolution. The occurrence was counted for each maximum height category neighboring within ±0.5°C of each grid point. The counts were then smoothed using a centered 9-point scheme and frequencies computed and contoured for each height category. Figures 5, 6, 7, and 8 show the contoured frequency fields for no echoes, short echo, medium echoes, and tall echoes, respectively. For the 1989 experiment, these frequency fields were used as though they were probabilities. Thus, if a particular day had a T_{CCL} of 18°C and a PB of 6.4°C, then the probability distribution for, no, short, medium, and tall echoes would be 12, 6, 6, and 76%, respectively. Therefore, maximum echo heights were forecast to be category 3, or tall echoes.

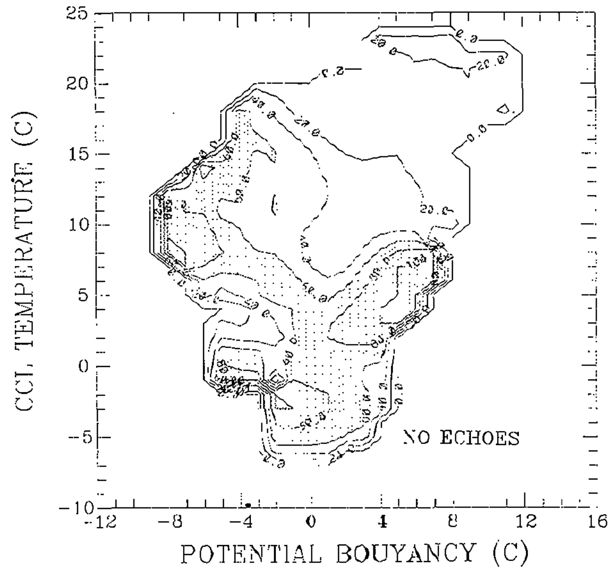

Figure 5. Discretized percentage of no echoes in the PB and T_{CCL} domain.

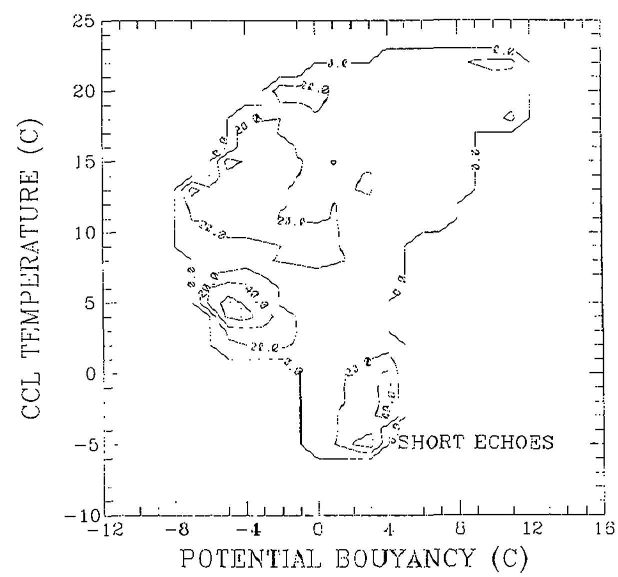

Figure 6. Discretized percentage of category 1 maximum echo top heights in the PB and T_{CCL} domain.

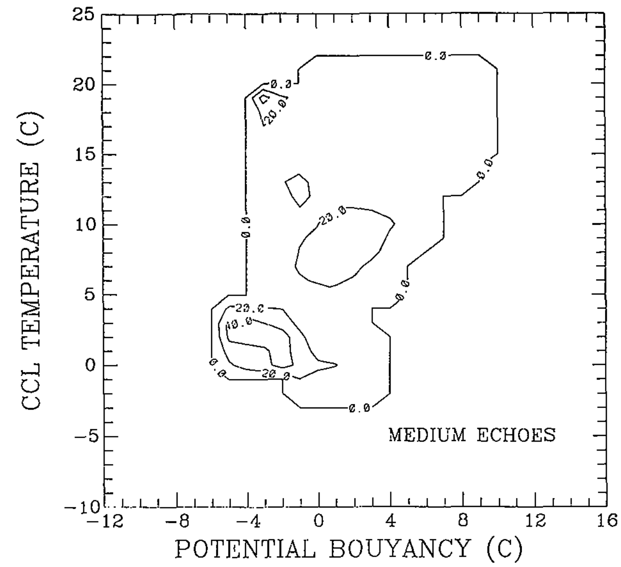

Figure 7. Discretized percentage of category 2 maximum echo top heights in the PB and T_{CCL} domain.

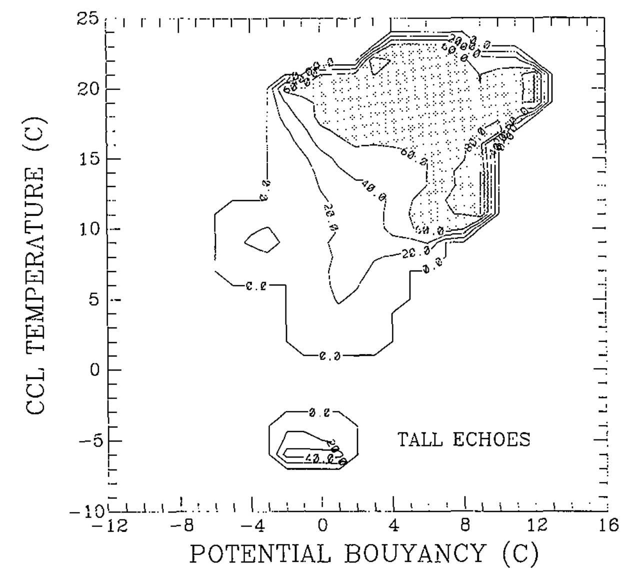

Figure 8. Discretized percentage of category 3 maximum echo top heights in the PB and T_{CCL} domain.

3.3 FORECASTING THE PRESENCE OF SUPERCOOLED RAIN DROPS

A forecast of the presence or absence of supercooled drops at the -10°C level was made using the discriminator function, *L*, for coalescence activity where

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

is a specific solution for Eq. 1. If the value of T_{CCL} and PB in Eq. 2 produced a negative value of *L*, which roughly corresponds to the region of open circles in Fig. 2, a forecast was made that supercooled drizzle and rain drops would be encountered during the mission in at least some updrafts at the -10°C seeding level. Otherwise, a forecast was issued that the presence of supercooled drops bigger than 300 μm diameter was not likely. Verification of this forecast was accomplished by keeping daily track of T_{CCL}. In-flight notes were made on the presence of supercooled drizzle rain drops based on visual observation of the size of splashes on the windshield of the airplane cockpit. The presence or absence, and concentration of supercooled drizzle and rain drops in updrafts at the -10°C level was quantified after the field program using 2D-C and 2D-P image records from optical array probes.

4. EVALUATION

The objective method was evaluated on the basis of weather that occurred during the 1 June to 5 August period of the 1989 PACE field experiment. Each of the three forecasts was evaluated separately. They are based only on data for only PIA, since SLO was moved to Paducah, Kentucky (PAH) just prior to the 1989 PACE field experiment. Table 1 summarizes each of the three daily objective forecasts and their corresponding verification. Under Forecast 1 values of T_{CCL} and PB are shown for PIA, along with the objective forecast from Fig. 4 (F_1), the objective forecast using Fig. 4 with precipitable water as an additional criteria (F_2), and the observed echo category (OEC) for the day; either tall (T), medium (M), short (S), or no echo (N) as defined by category 0 through 3. Beneath Forecast 2 in Table 1 is shown the objectively forecast probability distribution for no , short , medium, and tall echoes, along with the observed maximum echo top height (Max.) in 1000's of feet. Asterisks locate the probability category in which the observed maximum echo top occurred. Under Forecast 3 the calculated coalescence discriminator function *L* is listed along with the observed median concentration for the seeding mission of drops bigger than 300 μm at the -10°C level. Median values of $N_{D>300}$ given in Table 1 were determined from 2D-C and 2D-P image records, and apply only to updraft regions. Since operational procedures required that cloud penetrations be made shortly after cloud top ascended through the -10°C flight level, data in Table 1 for $N_{D>300}$ is representative of the results of precipitation processes which occurred in transport up from cloud base, although mixing and sedimentation can not be completely ruled out.

The performance of the technique to forecast Go (category 3), Stand By (category 2 and 3) and No Go days (categories 1 and 0) is summarized in Table 2. Days within each of the objective operational decisions (Go, Stand By, and No Go) were stratified by the tallest radar echo height within the target area observed from any of the 3 NWS radar sites during the operational period. Values of probability of detection and false alarm ratios for each forecast category were computed. Probability of detection was defined as $POD = \frac{\alpha}{(\alpha + \beta)}$, where α is the number of observed events correctly predicted by the

Table 1. Summary of objective forecasts and verifications for the1989 PACE field experiment.

	Forecast 1					Forecast 2					Forecast 3	
Date	T_{CCL}	PB	F_1	F_2	OEC	N	S	M	T	Max.	L	$N_{D>300}$
0601	18.0	6.4	GO	GO	T	12	6	6	76*	53	1.6	0.0001
0602	3.0	1.3	SB	NG	N	100*	0	0	0	0	7.8	-
0606	6.0	0.8	SB	NG	S	43	29*	0	29	19	4.0	-
0607	7.3	-0.4	SB	NG	N	78*	11	11	0	0	0.5	-
0608	8.3	0.7	SB	NG	N	18*	18	36	27	0	1.5	-
0609	2.7	2.5	SB	NG	N	100*	0	0	0	0	10.2	-
0610	2.4	1.7	SB	NG	M	100	0	0*	0	28	9.1	-
0611	3.4	-2.1	SB	SB	S	33	33*	33	0	15	1.7	-
0612	15.6	-0.7	SB	SB	M	50	50	0*	0	25	-8.2	1.10
0613	7.0	-4.9	SB	NG	S	0	0*	0	0	12	-6.8	-
0614	5.3	-2.9	SB	NG	S	50	50*	0	0	23	-1.8	-
0615	8.5	-5.8	NG	NG	S	100	0*	0	0	10	-9.9	-
0616	4.8	-2.1	SB	NG	S	75	25*	0	0	10	0.2	-
0617	4.7	-3.5	SB	NG	S	50	50*	0	0	17	-2.2	-
0618	9.9	1.1	GO	GO	S	13	20*	40	27	19	0.5	-
0619	13.7	-0.9	SB	SB	T	45	45	9	0*	42	-6.6	-
0620	8.6	1.4	GO	NG	N	8*	23	38	31	0	2.5	-
0621	11.3	5.1	GO	NG	N	14*	0	14	71	0	6.0	-
0622	14.5	2.9	GO	GO	M	19	19	16*	47	31	-0.9	-
0623a	15.8	4.8	GO	GO	T	19	12	12	56*	55	1.1	0.004
0623b	15.8	4.8	GO	GO	T	19	12	12	56*	55	1.1	0.003
0624	12.8	2.2	GO	GO	S	48	14*	5	33	24	-0.3	-
0625	11.3	2.4	GO	GO	S	35	6*	35	24	18	1.4	-
0627	12.9	0.1	GO	GO	T	46	15	8	31*	42	-4.2	0.67
0628	15.1	1.0	GO	NG	N	32*	19	10	39	0	-4.8	-
0629	-8.8	0.0	NG	NG	N	42*	21	8	29	0	17.5	-
0630	6.1	2.2	SB	NG	N	50*	17	0	33	0	6.3	-
0701	12.3	-0.3	GO	GO	M	88	12	0*	0	25	-4.3	-
0702	13.5	1.8	GO	GO	T	28	16	16	40*	39	-1.9	0.13
0703	9.9	2.4	GO	NG	S	0	8*	67	25	24	2.8	-
0704	12.3	4.5	GO	GO	N	17*	0	8	75	0	4.1	-
0705	2.4	2.8	NG	NG	N	100*	0	0	0	0	10.9	-
0706	11.1	2.6	GO	GO	N	30*	0	35	35	0	2.0	-
0707	9.2	6.7	GO	GO	T	0	0	0	0*	43	11.0	-
0708	13.8	8.2	GO	GO	T	0	0	0	100*	53	8.9	0.0
0709	16.8	5.6	GO	GO	N	14*	11	11	64	0	1.4	-
0710	5.6	10.6	GO	GO	N	0*	0	0	0	0	11.2	-
0711	17.9	7.2	GO	GO	T	5	10	5	80*	58	3.1	0.0
0712	16.0	2.5	GO	GO	T	16	18	12	55*	44	-3.2	-
0714	0.6	-0.4	NG	NG	N	0*	0	0	0	0	7.4	-
0715	-0.7	-2.9	NG	NG	S	100	0*	0	0	16	4.3	-
0716	6.1	-3.2	SB	NG	N	33*	67	0	0	0	-3.1	-
0717	9.3	-1.4	SB	NG	N	60*	10	20	10	0	-3.1	-
0718	11.2	-1.3	SB	SB	T	62	25	12	0*	37	-4.9	-
0719	15.8	2.3	GO	GO	T	12	19	12	57*	40	-3.2	0.03
0720	14.4	-1.2	SB	SB	M	40	50	10*	0	33	-7.8	-
0721	14.6	-0.2	GO	GO	T	58	32	5	5*	38	-6.3	-
0722	16.5	1.3	GO	GO	S	21	17*	7	55	21	-5.6	-
0723	16.2	3.5	GO	GO	M	20	17	13*	50	35	-1.5	0.40
0724	18.3	3.4	GO	GO	T	14	14	10	63*	49	-3.8	0.15
0725	18.7	3.6	GO	GO	T	12	10	12	66*	45	-4.0	0.08
0726	19.2	4.0	GO	GO	T	12	10	12	66*	37	-3.7	-
0728	17.8	4.0	GO	GO	N	18*	12	8	62	0	-2.4	-
0729	11.4	5.1	GO	GO	T	17	0	8	75*	43	6.0	-
0730	16.0	2.2	GO	GO	T	12	19	12	57*	47	-3.6	-
0731	14.5	0.4	GO	GO	N	42*	21	8	29	0	-5.2	-
0801	9.8	3.9	GO	NG	N	33*	0	33	33	0	5.6	-
0802	9.5	0.8	GO	NG	N	13*	20	40	27	0	0.5	-
0803	18.3	2.4	GO	GO	T	14	11	14	61*	53	-5.6	-
0804	18.1	6.2	GO	GO	N	12*	6	6	76	0	1.2	-
0805	14.8	6.7	GO	GO	T	0	33	33	33*	44	5.4	-

objective forecast technique, and β is the number of observed events not predicted. For example, Go forecasts had a POD of 81% in Table 2 from $\alpha = 21$ correctly predicted events (18 forecasts of Go when echoes taller than or equal to 36 kft occurred plus 3 forecasts of Go when echoes between 24 and 36 kft, non-inclusively, occurred), and $\beta = 5$ events not predicted (2 forecasts of Stand By when echoes taller than or equal to 36 kft occurred plus 3 forecasts of Stand By when echoes between 24 and 36 kft, non-inclusively, occurred). False alarm ratio was defined as $FAR = \frac{\gamma}{(\alpha+\gamma)}$, where α has the same meaning as that used in the definition of *POD*, and γ is the number of predicted events not observed. For example, Go forecasts had a *FAR* of 45% in Table 2 from $\gamma = 17$ predicted Go events which did not occur (12 forecasts of Go when no echoes occurred plus 5 forecasts of Go when echoes $\leq$ 24 kft occurred), and $\alpha = 21$ correctly predicted Go events.

As can be seen in Table 2, the use of PB and T_{CCL} with Fig. 4 performed fairly well at forecasting Go, Stand By, and No Go days. Of the 26 days on which at least medium sized echoes occurred in the target area during the operational period, 21 were predicted as Go days, a POD of

81%, with all of the remaining 5 days forecasted as Stand By. Correspondingly, the false alarm ratio for Go days was 45% (17 Go forecasts when short or no echoes occurred). That is, on all days having medium or tall clouds, the objective operational forecast procedure indicated that personnel should remain on-station and ready for duty.

Days having clouds with short echo tops or no echoes were not predicted nearly as well; the technique detected just 5 of the 35 days most unsuitable for experimentation for a probability of detection of just 14%, but there were no instances in which medium and tall clouds developed and a No Go objective forecast was made, resulting in a *FAR* of 0%. Thus, no opportunities to conduct missions on days with medium or tall echoes would have been lost if No Go objective forecasts would have been strictly followed. However, the technique was biased toward keeping people on-station on days when unsuitable or no convective clouds developed.

In the course of this evaluation, we found that the accuracy of No Go forecasts could be improved if precipitable water was included as an additional forecast parameter. Table 3 is similar to Table 2 except it summarizes an evaluation of Forecast 1 in which precipitable water, calculated for the 1000 to 500 mb layer using the PIA sounding, was used as an addition criteria. The procedure followed was to first use Fig. 3 to obtain a forecast of Go, Stand By and No Go. Then any Go or Stand By forecast which did not have a value of precipitable water greater than or equal to 26 mm was converted to No Go. The precipitable water threshold value of 26 mm was determined as an optimum value from an analysis of 1986 and 1987 NWS sounding and radar data, and was then applied to the 1989 data. As can be seen from Table 3, the probability of detecting a No Go day was greatly improved, increasing from 14% to 66% with one forecast of No Go when clouds suitable for experimentation developed. Thus, at least for the 1989 PACE field experiment, the objective technique provided a good indication of when and when not to keep project staff on-site. It also appears that the objective procedure to forecast convective occurrence can be improved for future convective cloud experiments, around Illinois and perhaps elsewhere, by including precipitable water.

Evaluation of the objective technique to quantitatively forecast maximum echo top height (Forecast 2 in Table 1) is summarized in Table 4. Verification of this forecast was limited to only days with echoes in the target area. As can be seen in Table 4, the technique performed fairly well at predicting tall echoes, forecasting 15 of 18 tall echo events correctly for a probability of detection of 83% and a false alarm ratio of 25%. The technique performed poorly at predicting short and medium height echoes, forecasting 7 days with short echoes when medium and tall echoes occurred, and 4 days with medium echoes when echoes less than 25 kft occurred.

Table 2. Evaluation of cloud occurrence forecast solely based on use of T_{CCL} and PB.

		Observed Height, kft				Skill, %	
		No Echoes	≤ 24	25-35	≥ 36	POD	FAR
Objective	Go	12	5	3	18	81	45
Forecast	Stand By	7	6	3	2	100	54
	No Go	3	2	0	0	14	0

Table 3. Evaluation of cloud occurrence forecast using T_{CCL} and PB with precipitable water.

		Observed Height, kft				Skill, %	
		No Echoes	≤ 24	25-35	≥ 36	POD	FAR
Objective	Go	7	4	3	18	81	34
Forecast	Stand By	0	1	2	2	96	32
	No Go	15	8	1	0	66	4

Table 4. Evaluation of the objective maximum echo top height forecast.

		Observed Height, kft			Skill, %	
		≤ 24	25-35	≥ 36	POD	FAR
Forecasted	Tall	3	2	15	83	25
Height	Medium	4	0	0	0	100
	Short	5	4	3	42	42

Finally, the ability of the technique to provide a forecast of the presence or absence of supercooled drizzle and rain drops at the -10°C level was evaluated. Figure 9 is a plot of the discriminator function L, specified by Eq. 2 versus concentrations of drops larger than 300 μm diameter as indicated by 2D-C and 2D-P image data for only the updrafts encountered during each mission to experiment with supercooled cumuli (open circles). Median values of the concentrations for each mission are denoted by the large vertically striped squares. Median values of drop concentration are best approximated by a 3rd order least squares polynomial equation

$$\log(N_{D>300}) = -3.5\times10^{-4} L^3 - 4.0\times10^{-2} L^2 - 5.4\times10^{-1} L - 2.1 \qquad (3)$$

where $N_{D>300}$ is the concentration of drops (per liter) greater than 300 μm diameter, and L is the value of the discriminator function (Eq. 2) calculated for each mission. The variance of this polynomial approximation was 0.40, the lowest variance for tests of polynomials of order 1 through 5. Hence, Eq. 3 is the best approximation to the data for a reasonably small order polynomial. Substitution of Eq. 2 into Eq. 3 yields

$$\log(N_{D>300}) = -10.0 - 2.3PB - 0.15PB^2 - 0.002PB^3 + 1.31T_{CCL} + 0.17PB\,T_{CCL} + 0.003PB^2\,T_{CCL} - 0.05T_{CCL}^2 - 0.002PB\,T_{CCL}^2 + .0004T_{CCL}^3 \qquad (4)$$

which yields supercooled drop concentration directly from values of PB and T_{CCL}. Equation 4 has been plotted as a solid line in Fig. 9 and runs approximately through the median values.

As can be seen in Fig. 9, supercooled drizzle and rain drops were encountered in the updrafts of clouds on almost every mission, and the concentraiton of large drops increases with decreasing L. The fact that no median values are plotted for values of L greater than approximately zero indicates that many of the updrafts on these missions had concentrations of supercooled drizzle and rain drops which were either less than 0.001 L^{-1} (i.e., effectively no precipitation-size drops).

Figure 9 shows the that median concentration of large supercooled drops encountered during any particular mission increases with decreasing values of L. The plot of Eq. 4 suggests that the concentration of large drops may begin to decrease as values of L exceed approximately -10, perhaps because it becomes more difficult to carry an increasingly massive water load aloft. Finally, if we choose to define the presence or absence of large drops by a threshold of 0.001 L^{-1}, then our observations are consistent with those determined for the Eastern Transvaal shown in Fig. 2. Therefore, it appears that L not only gave a good indication of the presence or absence of large drops, but also provided a good indication of the median

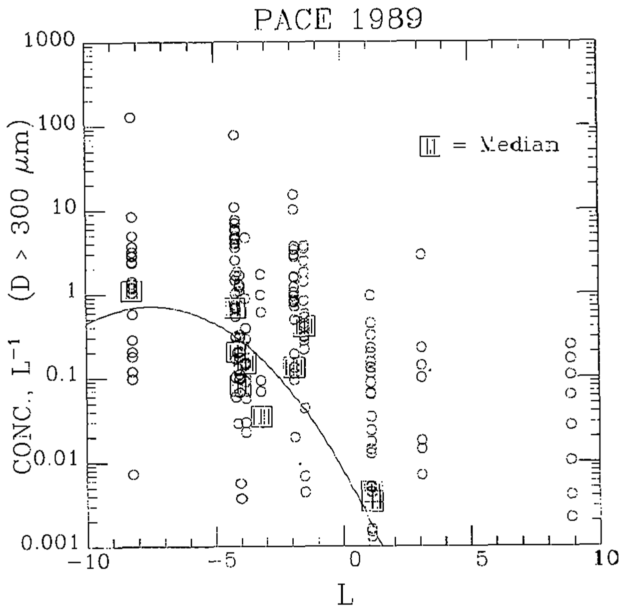

*Figure 9. Coalescence discriminator function **L** versus concentrations of drops greater than 300 μm in updrafts at the -10°C level of 1989 PACE clouds.*

concentration of large supercooled drops that were encountered in updrafts at the -10°C level of 1989 PACE clouds.

5. CONCLUSIONS

An objective technique which uses morning values of the T_{CCL} and PB to forecast the afternoon occurrence, maximum height, and activity of coalescence processes of convective clouds was developed and tested in the 1989 PACE field experiment. An evaluation of the technique showed that it performed well at forecasting occurrence of convection. The accuracy of the occurrence was improved if precipitable water was included as an additional criteria. It was also found that short, medium and tall maximum echo top heights in the experimental target area were related to T_{CCL} and PB, and that the maximum height of the convection in these categories was indicated by these two parameters. Finally, an empirically-derived discriminator function for coalescence activity, developed for warm-based clouds of a geographic region other than Illinois, not only performed well at providing an indication of the presence or absence of supercooled drizzle and rain drops at the -10°C level, but also was found to be correlated with median concentrations of supercooled drizzle and rain drops in updrafts of clouds measured by aircraft at the -10°C level during the 1989 PACE field experiment.

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