THE VARIABILITY OF CLOUD CONDENSATION NUCLEI AND CLOUD DROPLET POPULATIONS IN CONVECTIVE CLOUDS OVER THE HIGH PLAINS: HOW OFTEN ARE CONTINENTAL CLOUDS CONTINENTAL?

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Abstract. Observations and cloud microphysical modelling suggest that hygroscopic cloud seeding can be used to enhance precipitation from continental convective clouds. Model simulations demonstrate that the effect of such treatment varies with cloud microphysical characteristics. Significant enhancement is predicted for clouds with continental cloud droplet spectra, i.e. droplet concentrations on the order of 1000 cm^{-3}. The effect on maritime clouds with droplet concentrations of the order of a few 100's cm^3 or less is predicted to be much smaller. A survey of past studies of aerosols is presented along with a newly-assembled collection of observations of convective cloud droplet concentrations over the High Plains of North America. It is shown that while a majority of clouds are indeed microphysically continental, a significant fraction of clouds in this region have microphysical characteristics that are maritime or intermediate between maritime and truly continental. Practitioners of hygroscopic seeding in this region need to monitor aerosol and cloud characteristics and target microphysically continental clouds if they want to optimize the effects of their seeding. Furthermore, indiscriminant hygroscopic seeding of clouds or an evaluation of results without regard to the maritime or continental character of the target and control clouds could lead to inconclusive and/or spurious results.

1. INTRODUCTION

One general concept for modifying the precipitation produced by convective clouds is to in some way modify the microphysical evolution of the cloud so that more precipitation falls to the ground during the lifetime of the cloud or cloud complex. This may involve more efficient conversion of cloud water to precipitation as well as extending the size and/or lifetime of the cloud. The focus here is on the concept of seeding convective clouds with hygroscopic aerosols to increase precipitation. Several reviews over the past decade have covered this topic, including Czys and Bruintjes (1994), Bruintjes (1999), Silverman (2003) and National Research Council (2003). The specific focus here is the microphysical basis for precipitation enhancement by this method. The fundamental aim of hygroscopic seeding is to produce larger droplets more quickly that sweep out the naturally-nucleated smaller ones as they fall, thus to accelerate the growth of precipitation-size hydrometeors by collision and coalescence. In addition, hygroscopic seeding may influence supercooled cloud evolution in at least two ways. Production of a broader spectrum of cloud droplet sizes in mixed-phase cloud regions will lead to accelerated ice multiplication by the Hallett-Mossop rime/splintering process (Hallett and Mossop, 1974). In addition, larger precipitation-size liquid drops formed lower in a cloud by accelerated collision and coalescence, when carried above the freezing level, will freeze at lower altitudes (higher temperatures) and alter the vertical distribution of latent heat release, riming growth, and precipitation-loading (Beard, 1992).

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2. BACKGROUND

Biswas and Dennis (1972), Klazura and Todd (1978), and Todd and Howell (1982), among others, developed simplified quasi-steady-state one-dimensional models for understanding the situations in which seeding a convective cloud updraft with relatively large (~ 10 μm diameter or larger) water or salt particles will result in increased precipitation. This form of seeding introduces a population of large "collector" particles that accelerate the growth of precipitation-size hydrometeors by collision and coalescence. Reisin *et al*. (1996) more recently simulated this same process with a much more sophisticated time-dependent axi-symmetric cloud model with detailed treatment of aerosol and cloud microphysics, and full coupling between microphysics and dynamics. Issues typical to most cloud seeding concepts were addressed with these models, including optimum seed aerosol particle size and composition, mass of seeding material required, and the optimum timing and location for delivery of this material to clouds in various environments and states of development in order to produce the greatest enhancement in precipitation. These models were used to identify combinations of these factors that would in general lead to cloud-scale precipitation enhancement.

Of particular interest to the discussion here is how the variation in the background cloud condensation nucleus (CCN) population affects the simulated precipitation enhancement by hygroscopic seeding. In the model of Reisin *et al*. (1996) the concentration of active CCN varied with supersaturation as

(1)
$$N = C \cdot \left(\frac{S}{S_0} \right)^k$$

where N is cumulative concentration of CCN active at supersaturation S(%), in number per cm^3, S_0 is 1%, and C and k are constants. Clouds developed from a "continental" cloud condensation nuclei spectrum with C =1100 cm^{-3}, a "maritime" spectrum with C = 100 cm^{-3}, or an "intermediate" spectrum with C = 600 cm^{-3}, the number active at 1% supersaturation with respect to liquid water. They found that hygroscopic seeding with relatively large water or salt particles will enhance precipitation significantly in clouds with "continental" cloud droplet size concentration and size spectra, roughly doubling the precipitation produced without seeding. In the "intermediate" situation there was much more modest enhancement, and in maritime clouds there was negligible effect on precipitation.

In the 1990's Mather *et al*. (1997) in South Africa developed the concept of seeding convective cloud updrafts with low concentrations of much smaller hygroscopic particles (d ~ 1 μm) than had been used in previous hygroscopic seeding experiments. The concept is that these seed nuclei will nucleate droplets more readily than most of the natural aerosol particles, and these growing droplets will deplete the supersaturation in the updraft so that many of the natural aerosol particles never nucleate droplets. The result will be a lower concentration of cloud droplets with larger mean size and wider size dispersion than would have occurred naturally, leading to more rapid and efficient collision/coalescence growth of precipitation. This method involves dispersal of much smaller masses of hygroscopic material than does hygroscopic seeding with large nuclei or water droplets, and is logistically much less costly to implement.

Cooper *et al*. (1997) using a parcel model with detailed microphysics, and Yin *et al*. (2000) using the cloud model of Reisin *et al*. (1996), simulated the results of this method of hygroscopic seeding. With respect to the influence of the cloud droplet spectrum on seeding-produced precipitation enhancement, they found trends similar to those found earlier for hygroscopic seeding with relatively larger particles. Hygroscopic seeding with small particles produces significant enhancement of precipitation in "continental" clouds, and has little or no effect in "maritime" clouds.

While it is tempting to assume, based on these results, that hygroscopic seeding can be expected to produce significant precipitation enhancements in all clouds developing in very continental locations such as the High Plains of North America, observations of cloud condensation nuclei (CCN) spectra in this region in fact suggest otherwise. Hobbs *et al*. (1985a, 1985b) conducted several weeks of airborne observations of CCN activation spectra in the planetary boundary layer over regions from Great Falls, MT, to Big Spring, TX spanning the summers of 1975 and 1976. More intensive observations were conducted in the Miles City, Goodland, KS, and Big Spring areas. They fit their observed spectra to the form specified in Eq. (1), and divided their observed spectra into three composite classes with differing concentrations and rates of increase of concentration with increasing supersaturation. These classes were "maritime" with C=290 cm^{-3}, "transitional" with C=1500 cm^{-3}, and "aged continental" with C=2200 cm^{-3} (CCN active at 1% supersaturation). The slope k varied from 0.7 for "maritime" to 2.8 for "transitional" to 0.9 for "aged continental." Despite the geographically continental locations of the observations, "maritime" CCN spectra were observed 25% of the time. A terrain-follow-ing layer-averaged trajectory model was used to infer air mass origins. They found that "maritime" CCN spectra can be observed over the High Plains in maritime or modified maritime air masses, or in air masses that recently were involved in widespread cloud processes. In general, maritime air masses would become more continental in character within only a few days of travel over continental terrain in non-precipitating situations.

Vali *et al*. (1982) report an extensive series of surface CCN activation spectra acquired in June and July, 1976, in northeastern Colorado and southwestern Nebraska as part of the National Hail Research Experiment (NHRE). Among 60 observations at two sites over these two months, only 2 were characterized by a concentration active at 1% supersaturation as low as 300 cm^{-3}. These observations are characteristic of a predominantly "continental" CCN population, and suggest a much less frequent occurrence of "maritime" CCN populations at these sites during this time period compared to those observed by Hobbs *et al*. (1985b) over a longer time period and much larger geographic area.

Demott *et al*. (1996) in central North Dakota obtained CCN spectra on the ground and in the air, then compared CCN activation spectra to cloud droplet spectra observed within quasi-adiabatic updraft regions in convective clouds in the same region. Data were acquired over an 18-day period near Bismarck in July, 1993. For the period the average CCN concentration active at 1% supersaturation was 300 cm^{-3}. In addition, the cumulative frequency distribution of cloud droplet concentrations showed that droplet concentrations less than 300 cm^{-3} occurred in 25% of the samples obtained during this period. These observations show that “maritime” aerosol and cloud conditions can occur a significant fraction of the time in this region.

According to Eq. (1), the activated CCN concentration increases with supersaturation. When relating CCN population characteristics to cloud droplet concentration in clouds, one must have an idea of what typical supersaturations are reached in the clouds. In the simulations of Reisin *et al*. (1996), Cooper *et al*. (1997) and Yin *et al*. (2000), typically peak droplet concentrations were less than the specified concentration of CCN active at 1% supersaturation. Politovich and Cooper (1988) used updraft speed and cloud droplet spectra to infer that peak supersaturations were always less than 1%, and most of the time were less than 0.5%, in the lower regions of convective clouds in the Miles City area during the Cooperative Convective Precipitation Experiment (CCOPE) in 1982. In contrast, the cumulative frequency distribution of droplet concentrations in nearly adiabatic updrafts in clouds similar to those sampled by Politovich and Cooper (1988) compared to the cumulative frequency distribution of CCN active at various supersaturations in the work of DeMott *et al*. (1996) suggested that peak supersaturations reached in the updrafts in the Bismarck sample were as high as 2% much of the time.

Klazura (1971) observed precipitation particle size spectra (d > 250 um) using a foil impactor on an aircraft sampling in the upper regions of warm cumuli over southeast Texas during the summers of 1968 and 1969. Based on the number and size distribution of precipitation particles, he concluded that the population of clouds in the same region was much more “maritime” during one summer, and much more “continental” during the other.

In order to gain a better estimate of the fraction of the time that hygroscopic seeding of convective clouds can be expected to lead to significant precipitation enhancement, more observations and more refined modelling are needed. Based on the available modelling results, significant enhancement is expected when “continental” clouds are treated, and much smaller enhancement when “maritime” clouds are treated. While the definition of “maritime” is not precise, and varies from investigation to investigation, the trend of decreasing enhancements with more “maritime” microphysical conditions should be robust. The more microphysically “maritime” a cloud is, the smaller the enhancement of precipitation by hygroscopic seeding, other factors being equal.

Data on CCN concentrations and cloud droplet populations is difficult and expensive to obtain. It is clear from the work surveyed here that over the High Plains microphysically “maritime” CCN spectra and clouds occur with significant frequency, but that the characteristics of CCN and droplet populations can vary significantly between the same seasons in different years at one location, or in the same season and same year at different locations. Short periods of measurement at a few locations do not necessarily capture the complete range of variability. In order to make available more data with which to characterize the microphysics of High Plains convective clouds, presented here are observations of cloud droplet concentrations in clouds observed in some of the same regions discussed by Hobbs *et al*. (1985a), sampled during several subsequent field experiments using a different aircraft. While Hobbs *et al*. (1985a) used direct measurement of CCN to predict the character of clouds developing in the sampled air mass, this discussion will be based on in situ cloud microphysical observations.

3. DATA AND ANALYSIS METHODS

This study is based on cloud droplet data obtained with the Particle Measuring Systems, Inc. (PMS) Forward Scattering Spectrometer Probe (FSSP) carried by the South Dakota School of Mines and Technology (SDSMT) armored T-28 storm-penetrating research aircraft (Johnson and Smith, 1980; http://www.ias.sdsmt.edu/institute/t28/index.htm) during three field campaigns. These include the June, 1987, field season of the North Dakota Federal/State Cooperative Weather Modification Program (NDCWMP) at Dickinson, North Dakota (Detwiler and Smith, 1988); the Texas Experiment in Augmenting Rainfall through Cloud Seeding (TEXARC) at Big Spring in August, 1994; and the Severe Thunderstorm Electrification and Precipitation Study (STEPS) at Goodland in May and June, 2000 (http://www.mmm.ucar.edu/community/steps.html). Dickinson is ~260 km east of Miles City where Hobbs *et al*. (1985b) made extensive CCN observations in 1975 and 1976, and Goodland and Big Spring are the two other sites where they made extensive observations in 1975. All three locations are along the western edge of the High Plains region and are characterized by semi-arid summer climates.

The FSSP used in this study was serial number 1 of the commercial production run of this PMS instrument, first used in the field on the T-28 in 1975 during NHRE. It is a single particle counter. Particle size is inferred from intensity of light scattered into a photodetector with an annular mask admitting light scattered 8^o to 12^o from the forward direction. Probe circuitry is designed to reject data from particles which are not completely immersed in the sample volume. Data are accumulated for 1 sec (~100 m of aircraft travel) then dumped to the data acquisition system.

The probe was routinely calibrated with latex and glass spheres to verify the relationship between particle size and scattered intensity, taking into account the difference in index of refraction between the test particles and liquid water. This procedure was not applied until several months after the Dickinson field season (with the data being corrected after the fact), but was performed multiple times in the field during the Big Spring and Goodland field seasons. The integrated liquid water concentration also was compared to cloud water observations from a Johnson-Williams (JW) cloud water meter (Dickinson and Big Spring) and a Droplet Measurement Technologies (DMT) liquid water content probe (STEPS). Allowing for known response characteristics of the two probes, further adjustments were made in the FSSP size vs. intensity relationship to arrive at an optimum calibration such that the integrated FSSP cloud water concentration matched the observations from the direct total water measuring probes. (See Feind *et al*., 2000.) The Big Spring data were also reprocessed using a numerical simulation of the FSSP (Baumgardner and Spowart, 1990) in order to better refine size and concentration estimates. The reprocessed and standard data were very similar in character for that year, and in this study data from all three years are processed in the standard manner.

Of importance to the discussion below is the correction of observed concentrations for instrument dead time. The probe circuitry requires a small amount of time (several microseconds) to record data from each droplet passing through its sample volume. In regions of higher droplet concentration (exceeding several 100's cm^{-3}) a dead-time correction must be applied to account for droplets passing through the sample volume while the probe is recording data from the previous droplet and unable to respond. For the data discussed here, the dead time correction is one derived by PMS based on the fraction of time the probe circuitry is busy recording data. The raw concentration is divided by the factor

$$1-(0.55 \cdot \text{activity})$$

where activity is the fraction of the time during the current second that the probe is busy processing signals from droplets. As this factor is always less than 1 when droplets are present, it always results in an increase over the concentration based on the raw number of validly-sized droplets. Concentrations derived in this manner are in close agreement with the more rigorous model-based data reduction procedure discussed by Baumgardner and Spowart (1990) and applied to the Big Spring data, with the modeled concentration on the average 9% less than bulk correction concentration, with a root mean square difference of 35 cm^{-3}. While the absolute accuracy of FSSP droplet concentrations cannot be independently evaluated, similar concentrations obtained using two different processing schemes lends confidence to the relative concentration variations between updrafts.

Of possible significance in interpretation of the data presented below is an instrument refurbishment accomplished between the TEXARC project in 1994 and STEPS in 2000. Newer circuitry of the same design was installed, some of the optics was replaced, and the laser was upgraded. However, the same calibration procedures were successfully applied to data from all seasons and overall the data from different seasons appear to be consistent.

During all three projects, the mission of the T-28 was to sample growing to mature convective clouds or storms. Generally, isolated towering cumulus and cumulus congestus clouds were sampled at Dickinson and Big Spring, while larger more vigorous multicellular thunderstorms were sampled at Goodland. Typical sampling altitudes were 5 – 7 km MSL, with temperatures ranging from -5 C to -15 C, although occasional penetrations were made near cloud base. The sample size included here is fairly small. Presented below is a survey of two days including penetrations of three clouds with appropriate data from Dickinson, three days with a total of eight clouds from Big Spring, and seven days with seven thunderstorms from Goodland.

From the data collected on these days, passes through relatively precipitation-free updrafts were isolated using updraft speed estimated from aircraft motion, and PMS 2D-C cloud and precipitation particle imaging probe data. Peak cloud droplet concentration was extracted for each pass or pass segment corresponding to a region with a maximum in droplet concentration associated with a peak in the updraft and no precipitation or a minimum in precipitation particle concentration.

For these days reasonably representative proximity soundings based on radiosonde launches and the aircraft ascent and descent soundings are available. The observed cloud liquid water concentration is used to estimate how close to adiabatic the updraft conditions were by comparing to an estimate of adiabatic liquid water concentration derived from these soundings. The accuracy of these adiabatic cloud liquid water concentration estimates is difficult to assess. There are significant variations in boundary layer humidity on length scales of 100 km and time scales of hours, the typical separation in space and time between radiosonde sounding and sampled cloud. The representativeness of the sounding can be improved by modifying it using the aircraft ascent and descent temperature soundings. Humidity cannot be modified based on aircraft data as the T-28 carried no humidity sensor. Pilot observations of cloud base height are available in many cases, which further refines estimates of cloud base temperature. Finally, observed in-cloud temperatures are compared to those predicted by adiabatic ascent from the sounding convective condensation level. After arriving at a best estimate of cloud base conditions and penetration level temperature, an adiabatic liquid water concentration is found. Based on the maximum excess of any measured cloud liquid water concentration over the predicted adiabatic concentration (the theoretical maximum), estimates of adiabatic liquid water concentration were accurate to within 20%.

4. RESULTS

Figure 1 shows peak droplet concentrations in updrafts encountered in three cumulus congestus clouds during two days of operations during the NDCWMP near Dickinson as a function of fraction of adiabatic cloud liquid water concentration. For passes encountering more nearly adiabatic conditions, it is expected that the droplet concentration will more nearly represent the concentration of active CCN in the cloud base inflow air. The droplet concentration values exceeding 600 cm^{-3} are from one day, the lower values are from the other. Figure 2 shows the same relationship based on observations from eight cumulus congestus clouds observed on three days during TEXARC near Big Spring. The many nearly adiabatic observations are from two days, while the observations further from adiabatic conditions are from the third day. Finally, Figure 3 shows the same relationship for multiple penetrations of seven thunderstorms observed during STEPS near Goodland. Multiple updrafts were sampled within each storm.

There are several notable aspects of this relatively small sample, from 12 days during three different years at three different locations. Of the two days from Dickinson, one had a much more maritime character than the other. In Big Spring, most of the updrafts were more maritime than continental in nature. In Figure 2, the initial pass through the updraft with a peak concentration of nearly 600 cm^{-3} was followed by subsequent passes through the same updraft showing the same fraction of adiabatic water but peak concentrations of 340 and 430 cm^{-3}. Two other clouds sampled in the same region on the same day had peak concentrations less than 370 cm^{-3}. In Goodland, the droplet concentrations suggest a microphysically more continental cloud population in all storms sampled.

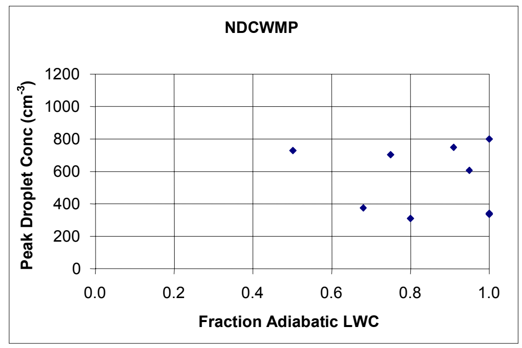

Figure 1: Peak cloud droplet concentration in updrafts from two flights during the NDCWMP as a function of the peak ratio of measured cloud water concentration to adiabatic water concentration within the updraft. The data were obtained in three clouds on two different days. The three lowest values come from the only cloud sampled on one of the days.

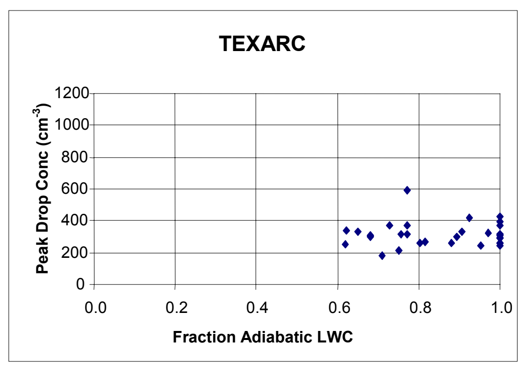

Figure 2: As in Figure 1, but based on observations from 8 clouds on 3 different days during TEXARC.

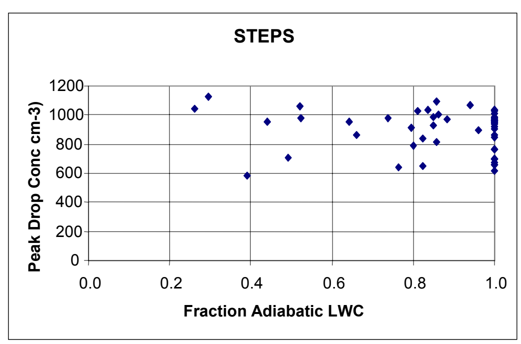

Figure 3: As in Figure 1, but based on observations from seven thunderstorms on seven different days during STEPS.

In all three locations the range of droplet concentrations does not vary significantly with the fraction of adiabatic liquid water. This suggests that in relatively precipitation-free updrafts, entrainment did not reduce peak droplet concentrations, within the accuracy of the methods used here for computing adiabatic liquid water concentration and measuring droplet concentration. On the scale of the droplet sampling, ~100 m, this is consistent with homogeneous mixing, where entrained dry air results in some evaporation of all droplets but disappearance of few.

In larger more vigorous storms, it is possible that more CCN are activated in stronger updrafts. Figure 4, based on TEXARC data, illustrates that peak droplet concentration was not a strong function of peak updraft speed. A similar pattern is seen in the STEPS data shown in Figure 5.

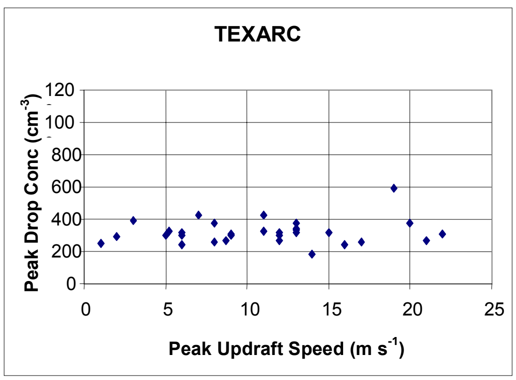

Figure 4: Peak cloud droplet concentration in updrafts sampled in 8 different clouds on 3 different days during TEXARC as a function of peak updraft speed in the updraft.

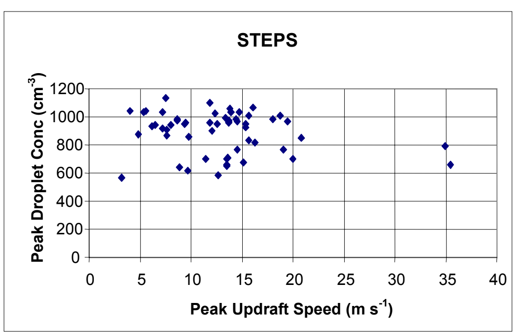

Figure 5: As in Figure 4, but for multiple updrafts in 7 storms during STEPS.

It would be desirable to characterize cloud microphysics using more than just the peak cloud droplet concentration. Maritime clouds also differ from continental ones in mean droplet size, and width of the droplet size distribution. Results of hygroscopic seeding will depend on these parameters, too. Peak concentration is used here because it is readily available from the three project data summaries, and because it is a relatively uncomplicated measurement. Cloud droplet size spectra must be computed from FSSP data with considerable care. In particular, even a well-calibrated FSSP yields noisy spectra when even small numbers of precipitation-size particles are present due to random sizing of irregularly-shaped (ice) particles or spherical particles larger than ~100 µm diameter (See Baumgardner and Spowart, 1990). Efforts will be continued to understand the microphysical character of High Plains convective clouds by extending this type of analysis to more seasons and locations, and by more carefully studying FSSP data from the projects discussed here as well as additional ones. In addition, air mass trajectory analysis like that performed by Hobbs *et al*. (1985a) will be a valuable tool for relating microphysical character to weather regime. Such a relationship will be a valuable guide for operational hygroscopic seeding.

5. CONCLUSIONS

If one looks at the set of peak cloud droplet concentrations from the NDCWMP, TEXARC, and STEPS, as a whole, on 8 out of 12 days the peak droplet concentrations clearly suggest microphysically "continental clouds". On 3 other days the peak concentrations are on the order of 300 cm^{-3} or less, approaching "maritime" in character. On one day during TEXARC, one cloud had much higher concentrations than two other clouds observed nearby.

Hobbs *et al*. (1985b) noted that the frequency of "maritime" CCN spectra, based on several weeks of sampling in two summers at several locations in the High Plains region, varied distinctly between the two summers. Atmospheric flow regimes can set up and persist for extended periods of time, subjecting a given region to a predominance of one air mass and/or weather type for weeks. In field projects of the type from which these data are drawn, several weeks of sampling will not characterize the complete range of variability observed over many years. Still, by using data accumulated over several weeks at three different locations in three different summers, it is shown that clouds that are microphysically maritime are observed a significant fraction of the time over various portions of the High Plains.

Modeling results of Reisin *et al*. (1996), Cooper *et al*. (1997), and Yin *et al*. (2000) suggest that enhancement of precipitation from convective clouds seeded with hygroscopic aerosols or droplets is much diminished the closer to maritime are the CCN supersaturation, and cloud droplet size, spectra. The data presented here support the conclusion of Hobbs *et al*. (1985b) that "maritime" CCN spectra, leading to microphysically “maritime” clouds, occur a significant fraction of the time over the High Plains. Operational seeding using hygroscopic aerosols should be targeted at clouds that are more continental in nature in order to optimize precipitation enhancement.

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