The Vertical Distribution of Aitken Nuclei in the Vicinity if Fort Collins, Colorado

By
August H. Auer, Jr.

Taken form thesis on partial fulfillment of the requirements
For the Degree of Master of Science
In Atmospheric Science
Colorado State University
Fort Collins, Colorado
June, 1965

Technical Paper No. 68
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ABSTRACT

Presentation is made of the vertical distributions of Aitken nuclei for the dates of 25 July, 29 July, 30 July, and 31 July 1964 in the vicinity of Fort Collins, Colorado. These nuclei counts were obtained by aircraft measurement from the surface (5000 feet MSL) to 12000 feet MSL. The nuclei distributions thereby obtained were then compared with other mean distributions over continental areas.

A small particle detector, type CN, manufactured by the Gardner Associates, Inc., Instrument Company, was used for counting the Aitken nuclei. Since the Gardner counter is calibrated only for sea-level conditions, a correction factor for varying altitudes was computed and applied to the instrument's readout to more accurately estimate the nuclei concentrations.

The results obtained from the limited sample suggest that the continental air masses over Fort Collins may be somewhat deficient in Aitken nuclei counts as compared to other continental areas.

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*Technical report to National Science Foundation under NSF Grant G-23706.

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INTRODUCTION

The physics of rainclouds is a subject of which our knowledge and understanding is expanding at an impressive rate, largely because of the possibility that, by suitable intervention on our part, a measure of control may be exercised over the weather. If this intervention is to be effective, then it must be based upon a sound understanding of the physical processes involved in cloud evolution and in the development of precipitation. This work is an attempt to place in perspective some recent measurements of the distribution of Aitken nuclei found in the vicinity of Fort Collins, Colorado.

The Plains area of northeastern Colorado exists as one of the maximum hail occurrence areas in the world. The purpose of this beginning research is to form a basis for eventually answering the question of whether or not cloud characteristics are any different over this region of maximum hail occurrence than the cloud characteristics over other continental regions.

The objective of this thesis is to present the vertical distributions of Aitken nuclei for the dates 25 July 64, 29 July 64, 30 July 64, and 31 July 64. These nuclei counts were obtained by aircraft measurement from the surface (5000 feet MSL) to 12,000 feet MSL. The nuclei distributions thereby obtained were then compared with published distributions.

REVIEW OF LITERATURE

Research pertaining to the vertical distribution of Aitken nuclei is rather limited, particularly in this country. Landsberg (1938) compiled the results of many thousands of observations, and gives some idea of the value of the Aitken countes in various environments. High counts are associated with human habitation and industrial activity, and the counts fall off, though not to zero, in regions remote from such centers. Table 1 gives the Aitken nucleus count in nuclei/cm^3 for elevations on a mountain slope based on 1190 observations.

TABLE 1

Aitken Nucleus Count in Nuclei/cm^3 for Elevations of Mountain Slopes (Landsberg, 1938)

Elevation	Average	Average Maximum	Average Minimum	Absolute Maximum	Absolute Minimum
1000-2000 m	2130	9830	450	37000	0
>2000 m	950	5300	160	27000	6

Falling counts on mountain slopes indicate the earth's surface to be the principal source of nuclei, and these few measurements have been supplemented by those taken by Wigand (1919) in balloon ascents and more recently by Weickmann (1957) from an aircraft, which show the same decrease in count with increasing altitude. The Wigand curve of Aitken counts as a function of altitude is well known but was obtained only during one or two free-balloon flights in central Europe.

Landsberg also gives a mean vertical distribution of Aitken nuclei based on data from 28 balloon ascensions in Europe; however, these counts run a little higher than the other mean curves studied. Most recent are the investigations of Weickmann. Weickmann's curve is an average of curves taken on twelve days of 1952-55 and indicates the general decrease of counts with height. These general observations support the theory that the majority of these nuclei originate at the earth's surface and are borne aloft by convection. The mean curves of the vertical distribution of Aitken nuclei are presented in Figure 1.

METHOD

A small particle detector, type CN, which was designed by the General Electric Company and manufactured by the Gardner Associates, Inc., Instrument Company of Schenectady, New York, was used for the counting of Aitken nuclei. The design of the Gardner detector approximates the Pollak nuclei counter (Fletcher, 1962).

To perform a count, the sample tube is flushed with the air to be measured. This sample chamber is a brass tube about 30 cm in length and lined with a wet blotting paper in order to saturate the sample of air before expansion. A second expansion chamber, of variable volume, is then brought to a desired partial vacuum pressure by means of a hand vacuum pump. A collimated beam of light is produced by a lamp and lens at the upper end of the sample tube, and its transmission through the chamber is measured by means of a

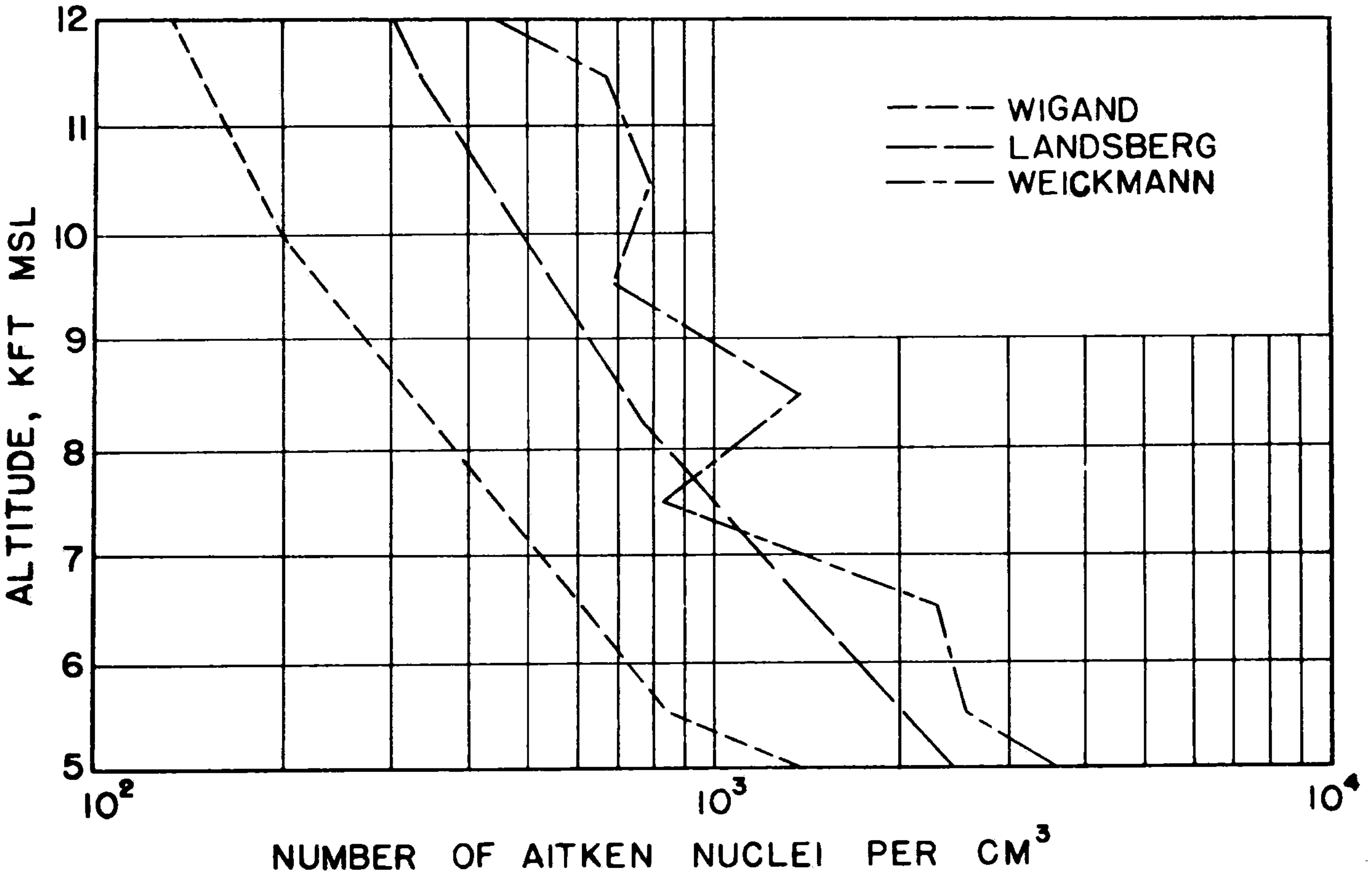

Fig. 1. Mean curves for concentration of Aitken nuclei at various altitudes according to Wigand, Landsberg, and Weickmann.

cadmium-selenium photocell in the base. About a half-minute is allowed for thermal equilibrium and vapor saturation to be attained in the sample chamber, and in this time the lamp current is adjusted to the "zero point" to give a standard photocell response. The underpressure is then released suddenly, by means of the exhaust tap, allowing for the adiabatic expansion and cooling. The resultant supersaturation yields a fog formed by condensation on the nuclei active at this supersaturation. The fractional change in photocell response is a measure of the fog density, and is termed the extinction. This extinction varies a galvanometer current, causing a needle deflection. The meter is calibrated so that relative numbers of particles per cubic centimeter can be read directly.

The resulting supersaturation is a function of the ratio of the sample and expansion volumes, the amount of partial vacuum pressure induced in the expansion chamber, and the ambient temperature (i.e., the saturation mixing ratio) in the sample chamber before expansion. For this experiment, the volume ratio was set at 3:1, the value of the partial vacuum induced in the expansion chamber was 15" Hg; and an average summertime lapse rate was used to approximate the temperature in the sample chamber at varying altitudes.

The saturation ratio was computed in the following manner:

$$S_r = \frac{P_f}{P_o}\left[\exp \alpha\, T_o \left[\left(\frac{P_f}{P_o}\right)^{.288} - 1\right]\right]^{-1} \qquad (1)$$

where

P_o is the initial ambient pressure in the sampler chamber,

P_f is the final pressure in the sample chamber after expansion, and

$P_f = P_o - \frac{15''\text{Hg}}{4}$,

$\alpha = \frac{\epsilon L}{RT^2_o}$ with $\epsilon = 0.622$, L the latent heat of condensation at temperature T_o (^{0}K), and R the gas constant for dry air.

The computed saturation ratios of the varying elevations are presented in Table 2. It can be seen that for this experiment the values of S_r ranged from 1.93 to 2.69. Since these saturation ratios are adequate to nucleate water droplets on all particles found in the air, the variation of S_r is of no importance except insofar as it affects the size of the droplets which form.

Since the Gardner counter is calibrated only for sea-level conditions and for full vacuum expansions, a correction must be applied to the instrument's readout to more accurately estimate the nuclei concentration. From Nolan and Scott (1964) comes the relationship

$$\frac{dI}{dy} = -n \pi \rho \, r^2 K(r) I \qquad (2)$$

where

I is the intensity of the light beam,

y is the length of the light beam,

n is the number of nuclei per gram of air,

ρ is the density of the air in the chamber after the wet adiabatic expansion.

r is the radius of the droplets, and

$K(r)$ is the scattering cross-section coefficient for water droplets in air.

Assuming that all droplets grow to the same size in the wet adiabatic expansion, we can say

$$\frac{4}{3}\pi r^3 n \rho_w = WF(r) \tag{3}$$

where

ρ_w is the density of water,

W is the amount in grams of water released in the wet adiabatic expansion per gram of dry air, and

$F(r)$ is the fraction of water going to the droplets. When the altitude is changing, the concentration and radius of the droplets are no longer functionally related to $F(r)$; therefore, we assume that $F(r)$ is a function of radius only. Solving for n from equation (3),

$$n = \frac{3}{4}\,\frac{WF(r)}{\pi r^3 \rho_w} \tag{4}$$

Now integrating equation (2) and substituting for the value of n found in equation (4), we find

$$\ln \frac{I}{I_o} = -\frac{3}{4}\,\frac{Wy\rho}{\rho_w}\,\frac{F(r)K(r)}{r} \tag{5}$$

where I_o is the value of the light intensity before expansion. The ratio of I/I_o is sometimes termed R; also the extinction, E, is defined to be $E = 1 - R$.

Nolan and Scott, assuming both no secondary scattering and that all water released in the adiabatic process contributes to the growth of the droplets (i.e., $F(r) = 1$) indicated a regular variation of $K(r)$ with r over the extinction ranges of 25% to 75%; this variation is characterized by $K(r) \alpha\ r^{-0.38}$. The assumption $F(r) = 1$ is true only for high concentrations of n resulting in high values of droplet surface area allowing none of the water released to diffuse to the chamber walls. Furthermore, for this experiment the extinction values frequently were less than 25%; hence it was felt that the Nolan and Scott approximation could not be used.

It now remains to obtain values for $F(r)/r^3$ versus $F(r)K(r)/r$ using equations (4) and (5). This comparison can be found only by substituting the original atmospheric conditions (1013 mb, 15-20^{0}C) under which the Pollak nuclei counter was calibrated. By using equation (4) and assuming variable values for n, we can determine the corresponding values of $F(r)/r^3$. From Pollak's original calibration, the number of nuclei/cm^3 and the respective extinction values are known. Using these extinction values in terms of I/I_O for the corresponding n assumed in equation (4), the only remaining unknown quantity in equation (5) is $F(r)K(r)/r$. Figure 2 shows the proportional relationship between $F(r)/r^3$ and $F(r)K(r)/r$; the value of $rF(r)^{-1/3}$ is plotted on the abscissa and the value of $K(r)F(r)^{2/3}$ is plotted on the ordinate. This relationship is over the ranges of extinction

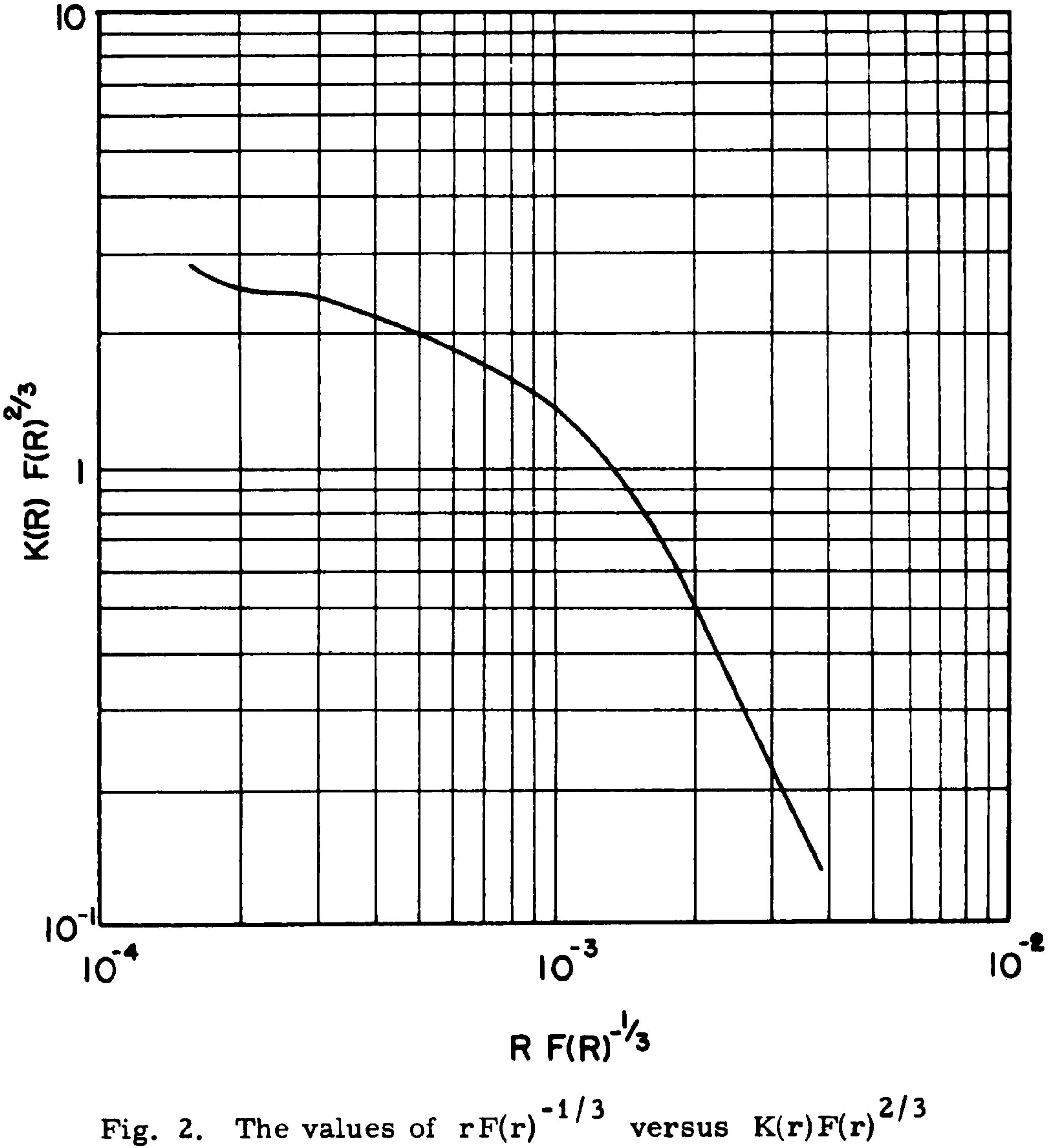

Fig. 2. The values of $rF(r)^{-1/3}$ versus $K(r)F(r)^{2/3}$ determined from equation (4) and (5) over the ranges of extinction E from 0.4% to 93.9%.

from 0.4% to 93.9%. As noted earlier, at high values of extinction (i.e., high concentration of droplets) the value of $F(r)$ is one, and the left hand side of Figure 2 becomes a plot of $K(r)$ versus r. At lower extinctions, the fraction of water released, $F(r)$, is proportional to the product of the concentration n and the droplet radius r; however, the variation of $F(r)$ in this region is complex, and its evaluation is uncertain.

Continuing with our calibration, it is now evident that the extinction for the Gardner counter can be corrected for the environmental conditions at higher altitudes than sea-level. Again, using equation (4), inserting the appropriate environmental values for W, and assuming variable values for the concentration n, $F(r)/r^3$ or $rF(r)^{-1/3}$ may be determined for the new elevation. Reference now to Figure 2 will yield a value for $K(r)F(r)$ or $F(r)K(r)/r$ allowing the determination of the I/I_o (hence extinction) on the Gardner counter by means of equation (5). Now using the Gardner counter calibration of Rich, again the extinction is related to the number of nuclei/cm³, N_o.

The concentration n (nuclei/gram) may be expressed in nuclei/cm³ by muliplying by the appropriate environmental density; i.e., $N = \rho n$. The relationship between N and N_o (as outlined above) is shown in Figure 3 for the altitudes of 5000 feet and 12,000 feet MSL. The abscissa is the value of the concentration, N_o (nuclei/cm³), as read on the Gardner counter; the ordinate is the

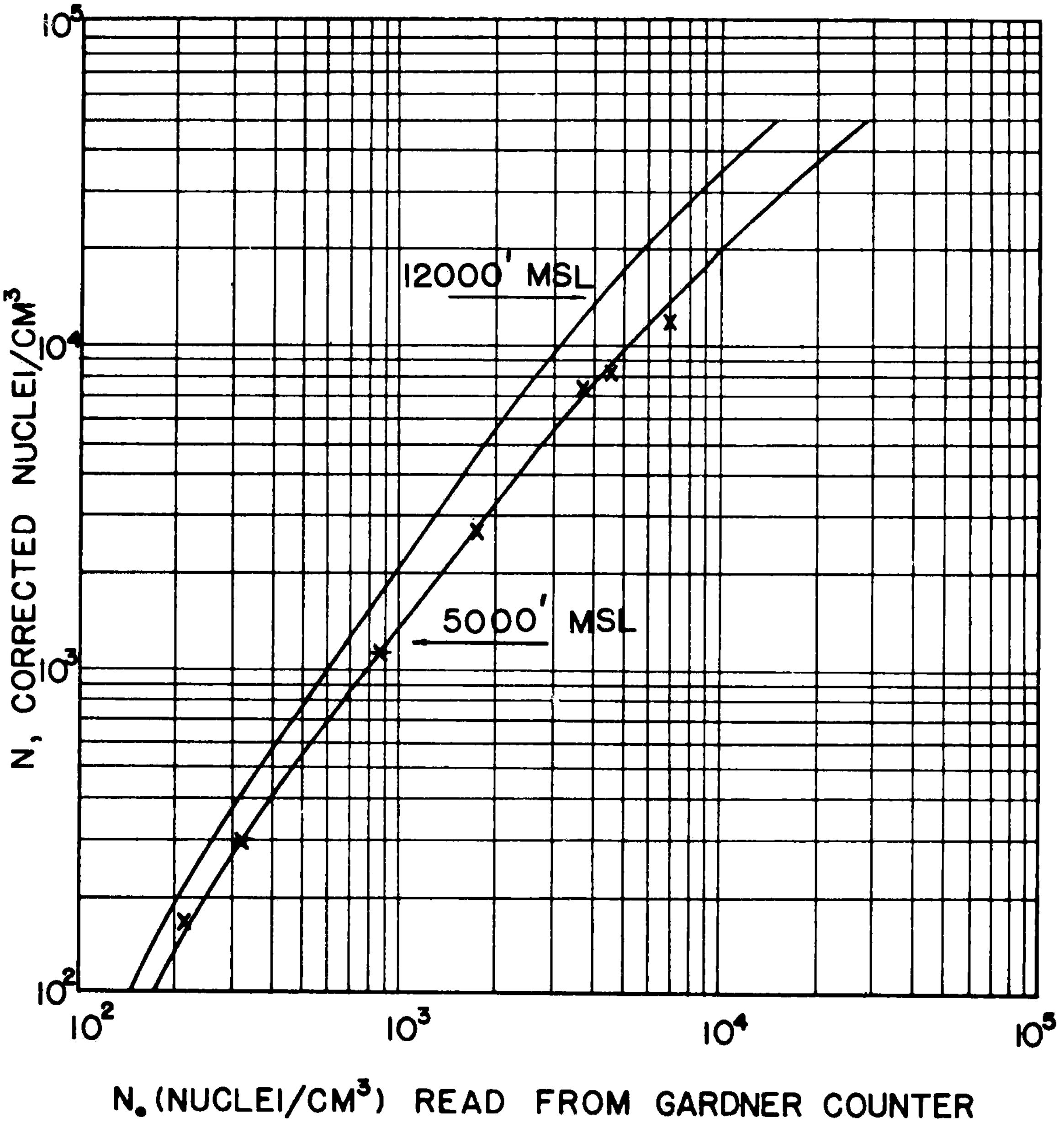

Fig. 3. The nuclei concentration correction curves for use with the Gardner counter at altitudes of 5000 and 12000 feet MSL. The "x" data points correspond to observational data used in testing the correction curve.

value of the corrected estimate concentration, N(nuclei/cm^3). For example, a sample of air indicating 10^3 nuclei/cm^3 at 5000 feet MSL would stand corrected at 1.3×10^3 nuclei/cm^3. It can be seen that at 5000 feet MSL for values of $N_o < 5 \times 10^2$, the Gardner counter is reading concentrations too high. All other regions on both the 5000-foot and 12,000-foot curves require a positive correction to be added to the observed Gardner counter concentrations to obtain a more reasonable estimate of the nuclei concentration.

This theory was tested by Dr. Pat Squires (NCAR, Boulder, Colorado) and the author utilizing a Pollak counter and a Gardner portable counter in which nuclei concentrations from identical samples of air were observed. The Pollak nuclei counter was operated under standard sea-level atmospheric conditions; the Gardner counter was operated under normal 5000-foot MSL atmospheric conditions. Hence the values of N versus N_o could be compared. The results of the experiment are shown by the "x" data points on the curve in Figure 3. The agreement is rather good, particularly in the regions of low extinction values. While no such tests was performed at the 12,000-foot level, it is assumed that such correlation would also hold true.

Table 2 lists the atmospheric parameters utilized in the computation of the correction factors.

TABLE 2

Atmospheric Parameters Used in Gardner Counter Calibration

Elevation Kft	Pressure mb	Temp. ^0C	Super-saturation ratio	Water Release g/g	Air Density g/cm^3
5	850	20	1.93	3.5×10^{-3}	1.00×10^{-3}
6	812	17	2.00	3.4×10^{-3}	0.97×10^{-3}
7	782	15	2.10	3.2×10^{-3}	0.96×10^{-3}
8	752	12	2.21	3.1×10^{-3}	0.91×10^{-3}
9	724	10	2.31	3.0×10^{-3}	0.89×10^{-3}
10	697	7	2.40	2.9×10^{-3}	0.87×10^{-3}
11	670	5	2.56	2.8×10^{-3}	0.82×10^{-3}
12	640	0	2.69	2.7×10^{-3}	0.80×10^{-3}

Accuracy of the instrument is difficult to assess precisely, but the error should lie within 30% according to the General Electric Company (Rich, 1965).

By measuring the supersaturation necessary for condensation, it is possible only to infer the size spectrum of the nuclei under the assumption that there is an unequivocal relationship between the nuclei size and the supersaturation and that the supersaturation in the nuclei counter is correctly computed from the expansion. Earlier observations and recommendations (Junge, 1951; Mason, 1957; and Rich, 1965) indicate that for the supersaturation ranges attained in this experiment (193-269%) Aitken nuclei radius 10^{-7} cm or larger were detectable. Such supersaturations are sufficient to activate almost all the naturally occurring nuclei, with the exception of small ions. There is some possibility that the largest nuclei may be lost by sedimentation before the count is made, but their relative concentration is usually so small that this has a negligible effect on the final count. The Aitken count may thus be taken as a measure of the total number of nuclei present in the atmosphere.

In order to obtain the airborne Aitken nuclei counts, the Gardner counter was installed aboard a modified North American SNJ-3 a weather reconnaissance aircraft commissioned by the Colorado State University Hail Suppression Project. A non-contaminated air sample was fed into the counter by means of a 20-foot length of 1/4" Tygon tubing with its open end installed midway beneath the left wing. This position provided an air sample which was not contaminated by the single engine exhaust.

Sampling flights were conducted on the mornings of 25 July, 29 July, 30 July, and 31 July 1964. A departure time of 1000 MST was set each day; it was thereby assured that the surface inversion was destroyed. The weather for all flights was clear with only scattered cumulus over the mountains. The flights encompassed an area of approximately 1450 square miles. When the entire area was sampled at an altitude of 7000 feet MSL, then the aircraft climbed slowly to 12,000 feet MSL and then descended again over the portion of the sampling area directly east of Fort Collins. Examples of the flight plans and the nuclei counts obtained are shown in Figures 4-7.

Only an average of the "background" Aitken nuclei counts were used in determining the vertical distribution of the nuclei. These averages consisted of the point observations of Aitken nuclei counts taken at the varying altitudes. Samples reflecting the high concentration of Aitken counts due to human or industrial pollution were disregarded. Generally these were the low-level airborne samples taken just downwind of Fort Collins and the Denver-Boulder areas.

Flights of 25 July and 29 July sampled the areas south and east of Fort Collins; the flight of 30 July sampled the area north and east of Fort Collins, while the flight of 31 July southeast of Fort Collins was abbreviated due to the development of possible hail suppression activity.

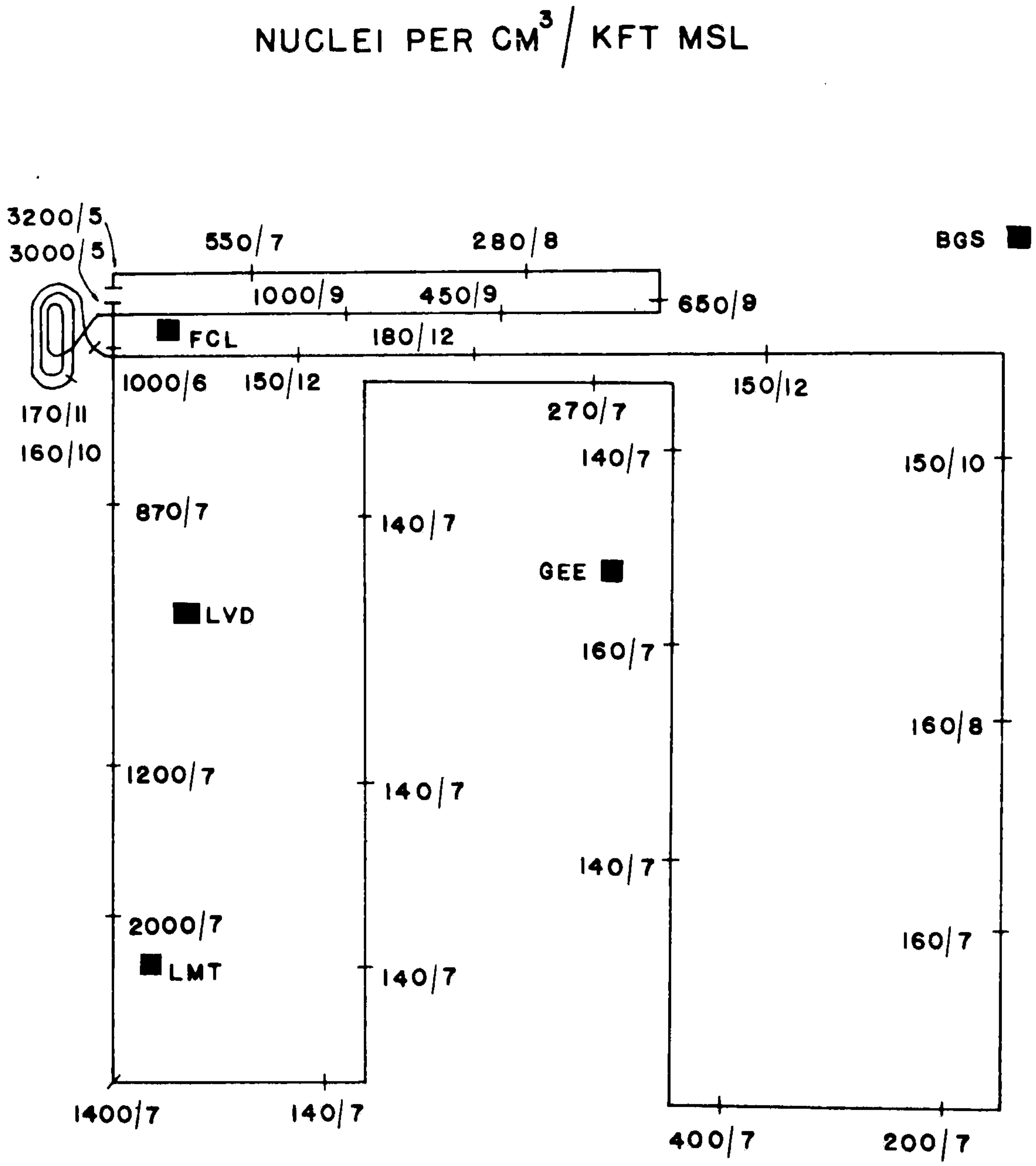

Fig. 4. Track of sampling aircraft on 25 July 64. Scale: 1" equals 8 n. mi. Observations are in units of Aitken nuclei concentrations per cm^3 at thousands of feet altitude MSL.

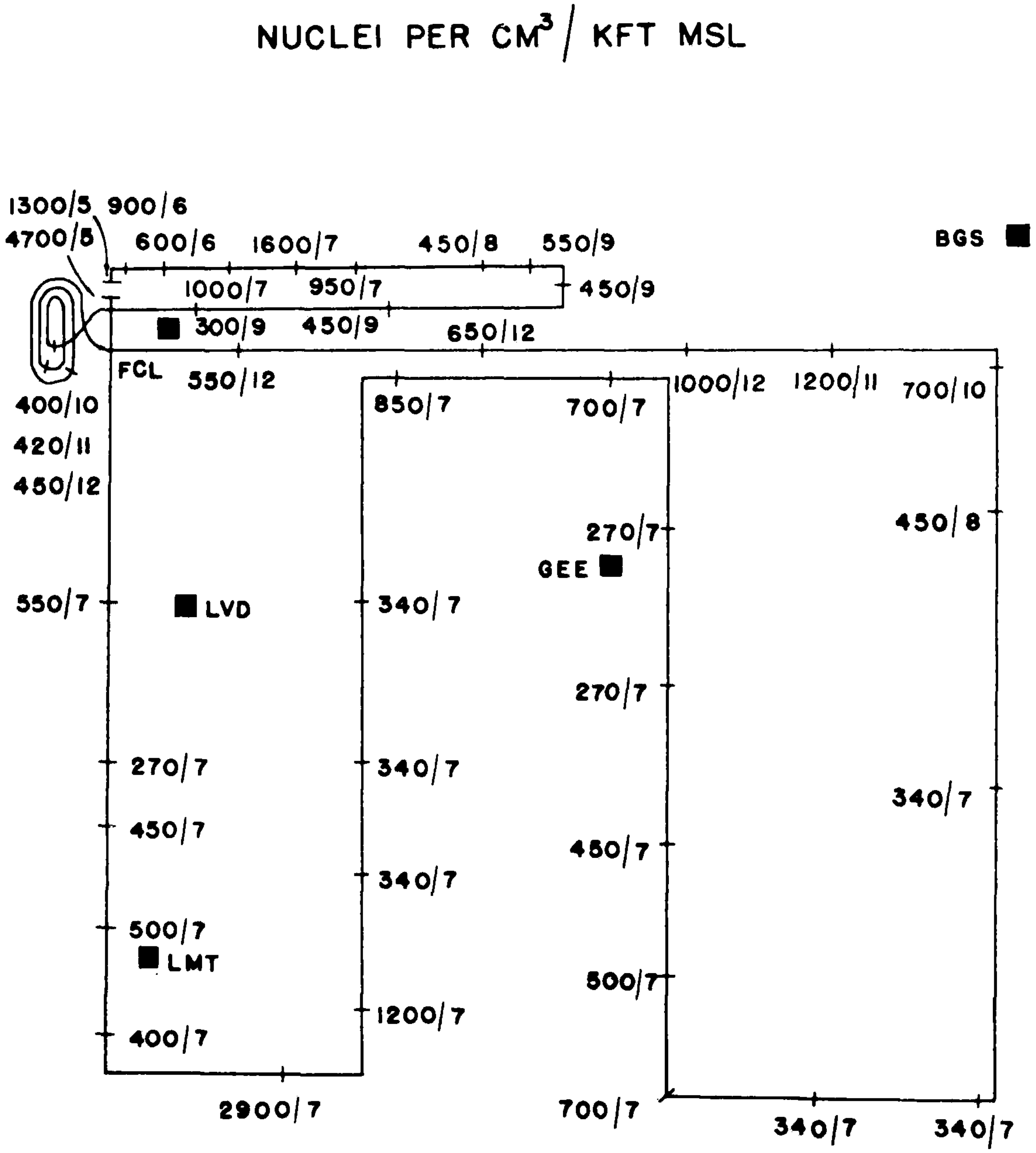

Fig. 5. Track of sampling aircraft on 29 July 64. Scale: 1" equals 8 n. mi. Observations are in units of Aitken nuclei concentrations per cm^3 at thousands of feet altitude MSL.

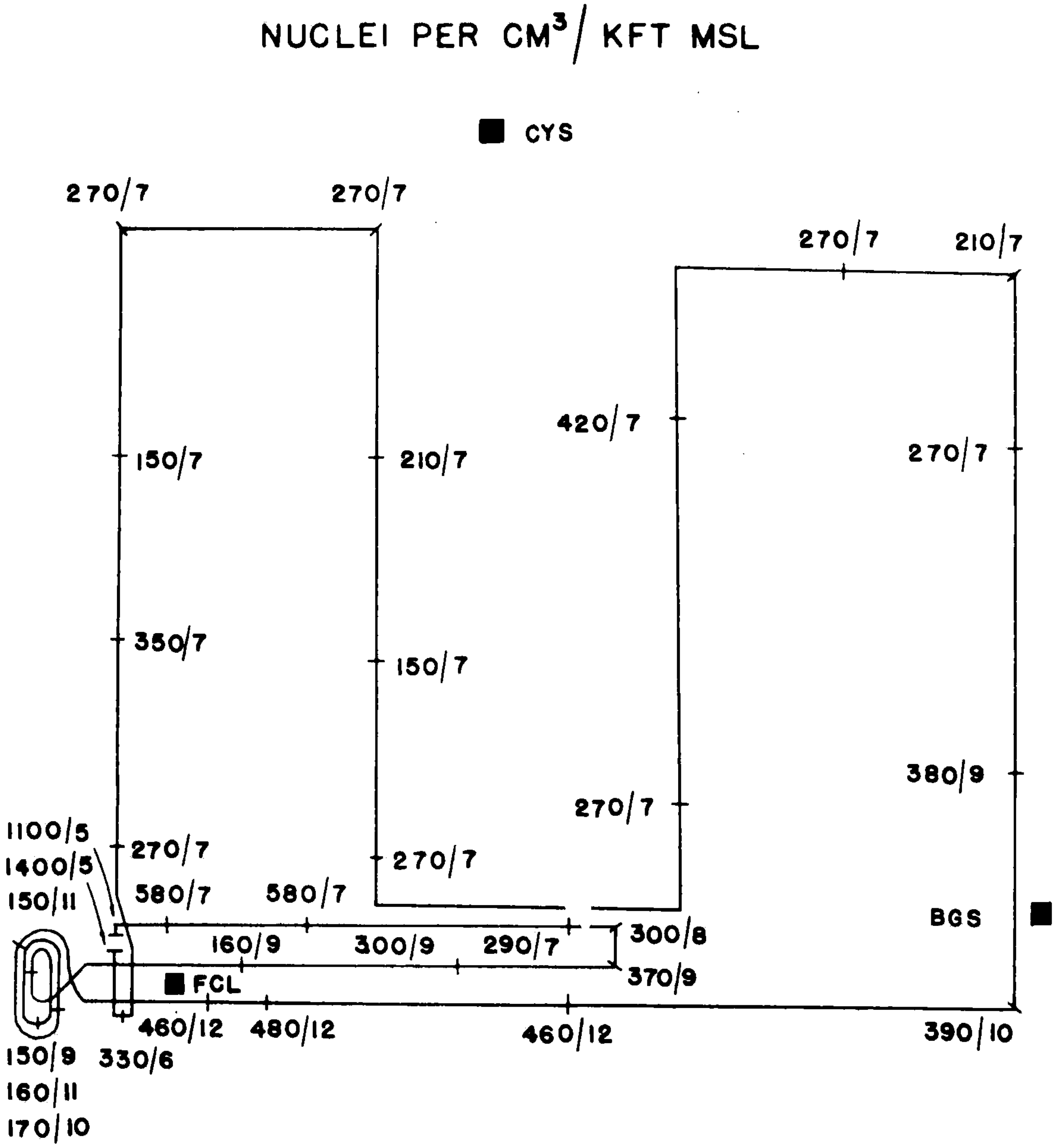

Fig. 6. Track of sampling aircraft on 30 July 64. Scale: 1" equals 8 n. mi. Observations are in units of Aitken nuclei concentrations per cm^3 at thousands of feet altitude MSL.

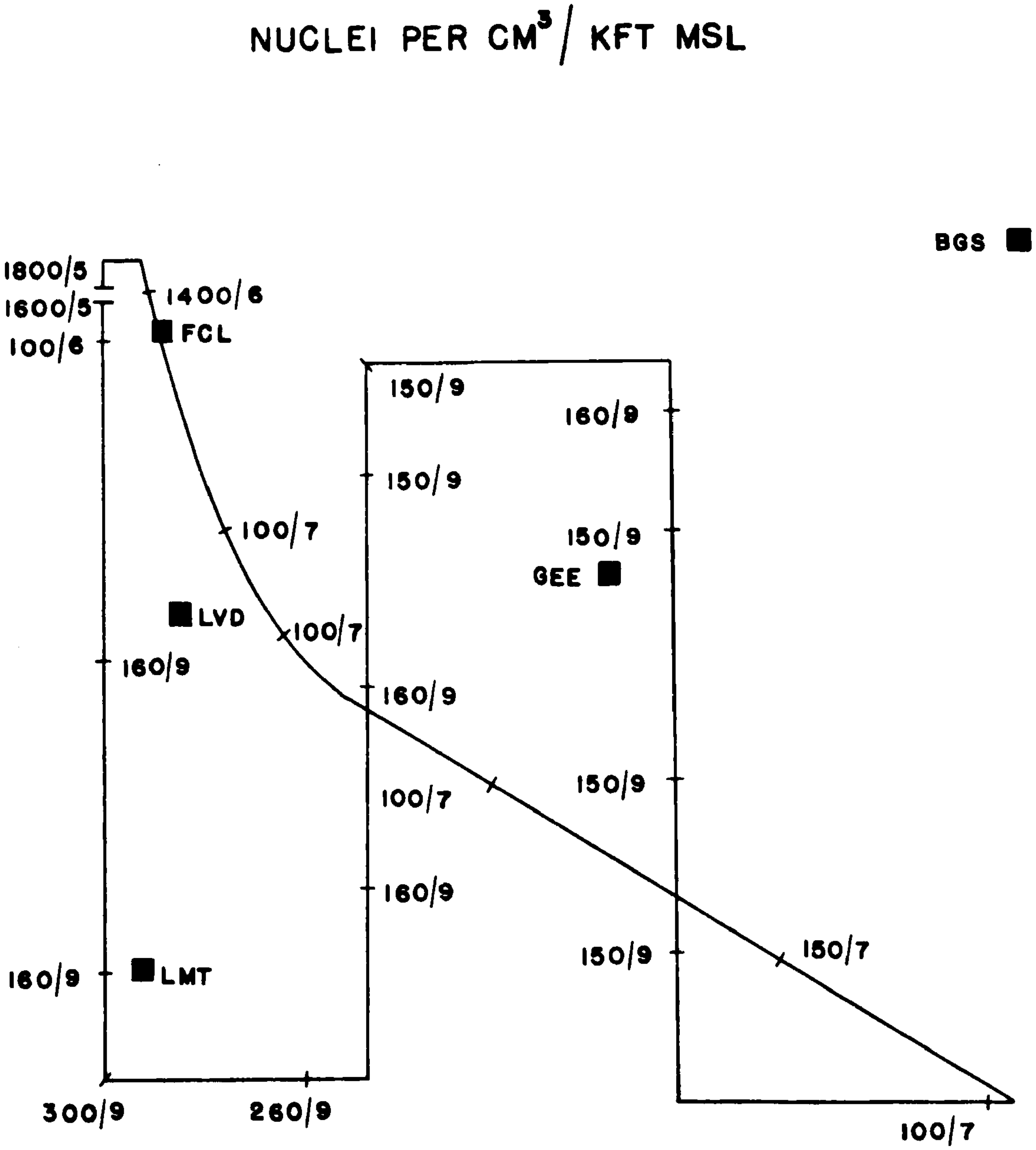

Fig. 7. Track of sampling aircraft on 31 July 64. Scale: 1" equals 8 n. mi. Observations are in units of Aitken nuclei concentrations per cm^3 at thousands of feet altitude MSL.

CONCLUSIONS

The vertical distribution of the Aitken nuclei counts in the vicinity of Fort Collins are shown in Figures 8-9. It can be seen that nuclei concentrations at all levels vary somewhat over the four days sampled. The wind profiles from the Denver, Colorado, 0500 MST rawinsonde are also found in Figures 8 and 9. These wind profiles have been included to provide an indication of the prevailing air mass over Fort Collins at the time of sampling. It can be seen that on 25 July 64, light and variable winds were prevailing; hence, a stagnant air mass. Thus the Aitken nuclei distribtuion over Fort Collins may be considered as one due to local environmental contamination. In the case of 29 July 64, the Aitken nuclei counts are increased with the accompanying south to southwest flow at all levels. The change to north-northeasterly winds on 30 July 64 brought a slight decrease in the Aitken nuclei counts throughout the sounding. On 31 July 64, when the winds again did become southwesterly at moderate summer-time speeds, the Aitken nuclei concentrations were still small. The sampling was incomplete due to the abbreviated flight, but the increase in concentration between 7000 feet and 8000 feet MSL is encouraging in view of the existing southwesterly flow. During all flights the only clouds observed were small cumulus over the mountains, and occasionally a small weak cumulus developing overhead. From this limited sample, there appears a tendency for increasing the local Aitken nuclei concentration when accompanying winds are from the

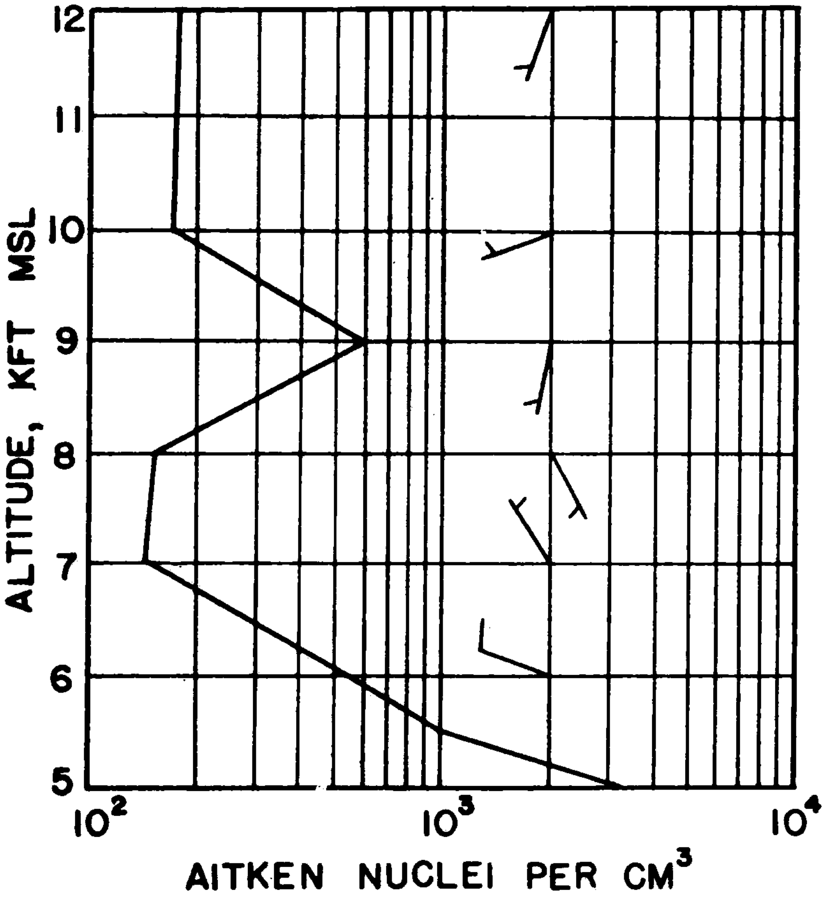

Fig. 8a. Vertical distribution of Aitken nuclei in the vicinity of Fort Collins, Colorado, on 25 July 64. Wind data are from DEN 0500 MST rawinsonde.

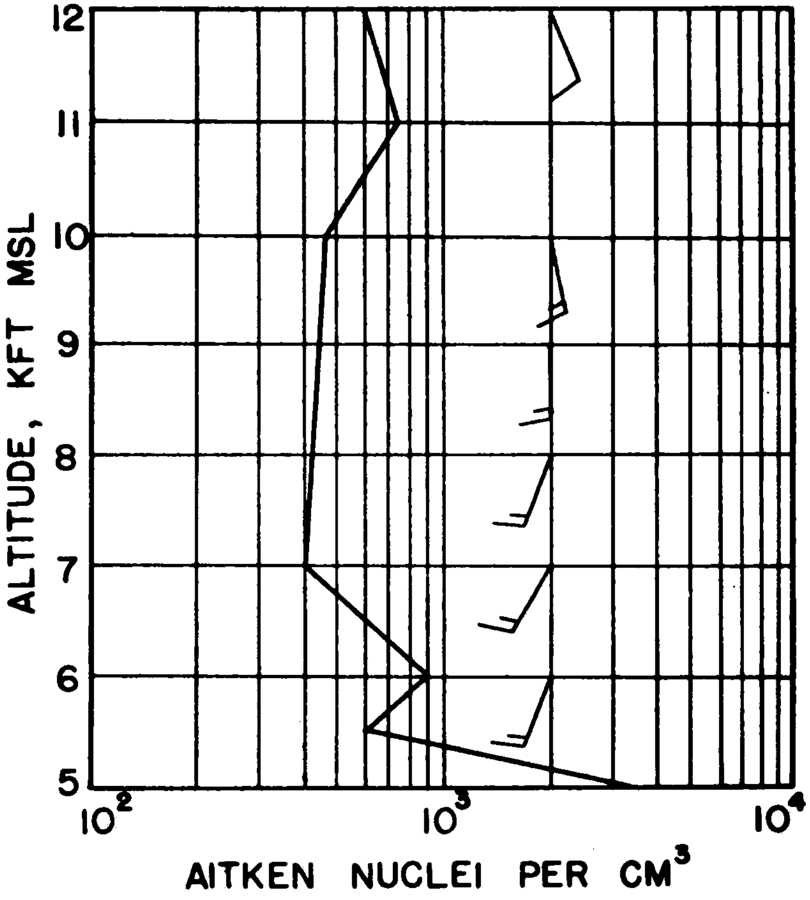

Fig. 8b. Vertical distribution of Aitken nuclei in the vicinity of Fort Collins, Colorado, on 29 July 64. Wind data are from DEN 0500 MST rawinsonde.

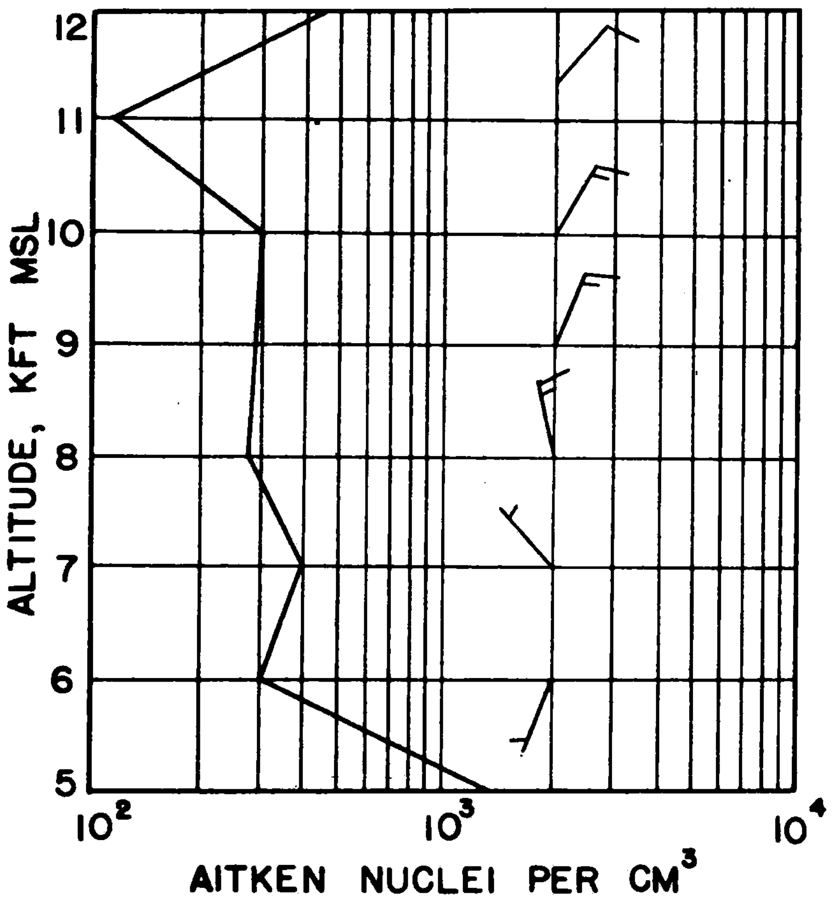

Fig. 9a. Vertical distribution of Aitken nuclei in the vicinity of Fort Collins, Colorado, on 30 July 64. Wind data are from DEN 0500 MST rawinsonde.

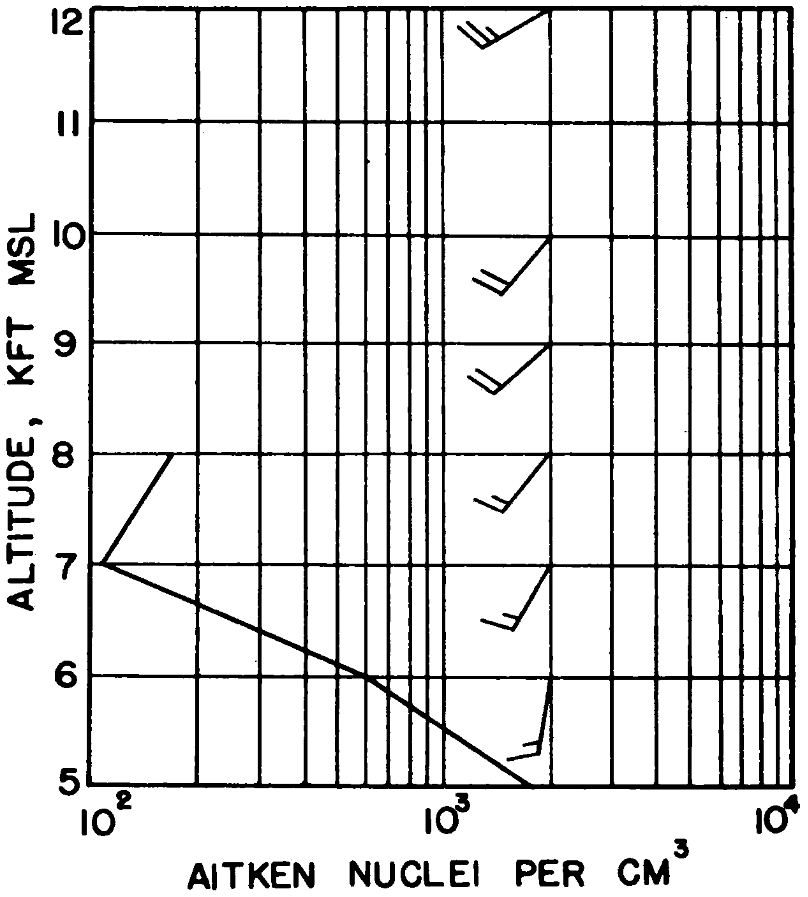

Fig. 9b. Vertical distribution of Aitken nuclei in the vicinity of Fort Collins, Colorado, on 31 July 64. Wind data are from DEN 0500 MST rawinsonde.

Average Concentration of Aitken Nuclei in the Vicinity of Fort Collins, Colorado

Elevation feet, MSL	Nuclei/cm^3 N	Nuclei/gram n
5000	2200	2.2×10^6
6000	600	6.2×10^5
7000	250	2.6×10^5
8000	220	2.4×10^5
9000	360	4.0×10^5
10000	310	3.6×10^5
11000	320	3.9×10^5
12000	410	5.1×10^5

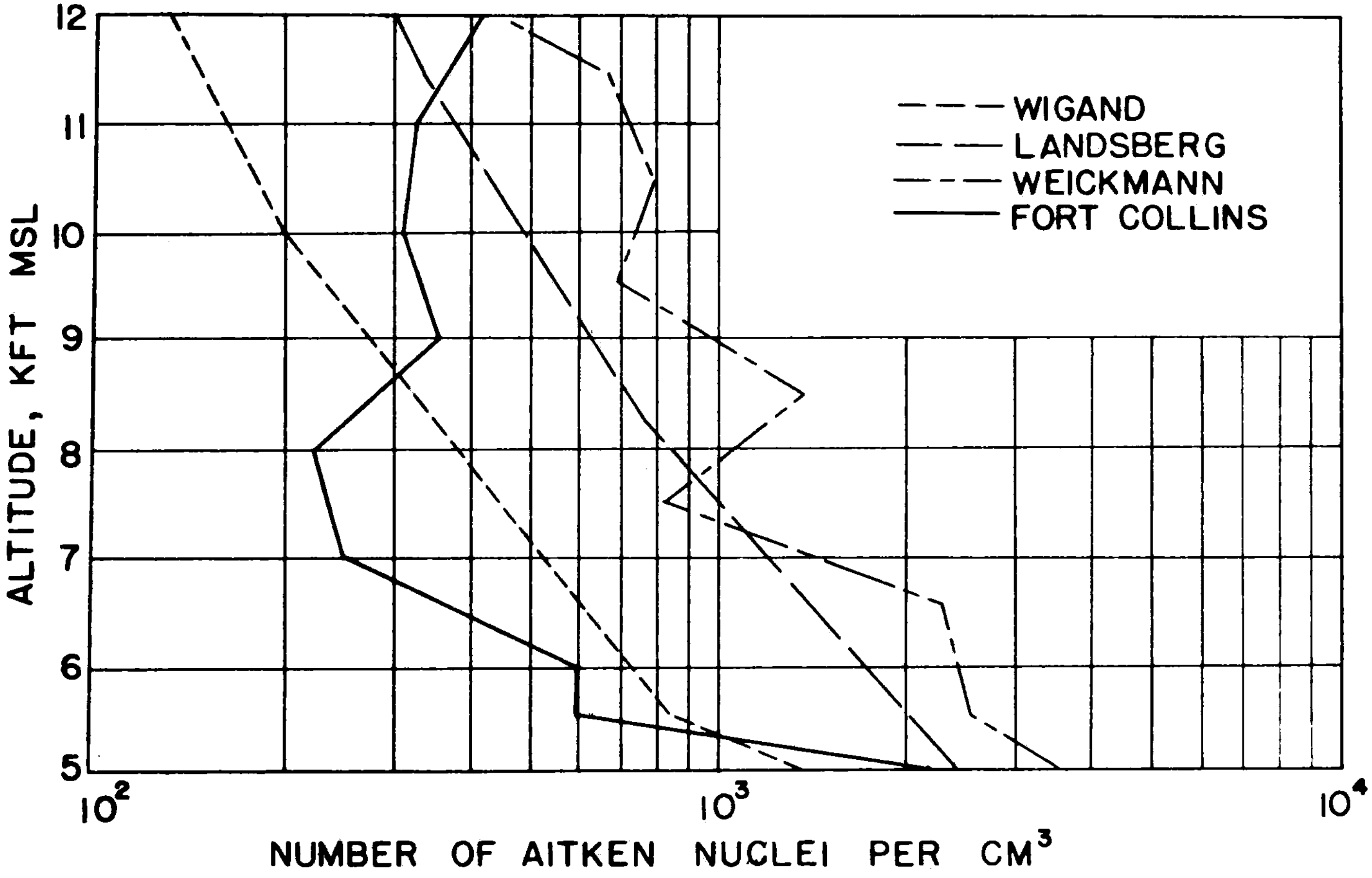

Fig. 10. Comparison of the mean curve for concentration of Aitken nuclei at various altitudes as found in the vicinity of Fort Collins, Colorado, with the mean curves of Wigand, Landsberg, and Weickmann.

southwest. Likewise the presence of northwesterly flow seems to decrease the counts slightly. More positive conclusions can result only from continuing climatology.

Table 3 gives the average concentrations of Aitken nuclei in the vicinity of Fort Collins expressed both in units of nuclei/cm^3 and nuclei/gram of air. It seems more appropriate to express the nuclei concentrations in number per gram, especially at higher altitudes, because of the change in density and insignificance of unit volumes.

Figure 10 compares the mean vertical distributions of Aitken nuclei in the vicinity of Fort Collins with the mean distributions of Wigand, Landsberg, and Weickmann. All the curves for comparison originated at sea-level; the Fort Collins curve originated at 5000 feet MSL since that is the ground elevation. It would therefore, be expected that the Aitken concentrations at 5000 feet for Fort Collins should be higher because of the contaimination of the earth's surface. However, such is not the case when the Fort Collins curve is compared with the two most recent sets (Landsberg and Weickman) of Aitken nuclei distributions. Furthermore, the vertical sounding of the Aitken nuclei counts over Fort Collins is consistently lower in these two comparisons below 8500 feet MSL, and only raises above the average sounding of Wigand above 8500 feet MSL. The concentration of Aitken nuclei from 6000 feet MSL to 12,000 feet MSL at Fort Collins varies only between 200 and 600 nuclei/cm^3. This reflects minor agreement with the mean distribution of cloud droplet concentrations of magnitudes 400 to 1000 droplets/cm^3 as found in small cumulus in this region by Eaton (1963); however, it is not certain where the air comes from that forms the clouds. One explanation of the Fort Collins distribution is that possibly the small nuclei counts may be representative of the nuclei content of air over the mountains west of Fort Collins; the air, brought to lower elevations by katabatic winds, may not yet be contaminated by the surface of the earth through strong convection which would appear later in the afternoon.

It therefore appears evident that, in the vicinity of Fort Collins for the four days sampled in late July, that the number of Aitken nuclei in the atmosphere from the surface (5000 feet MSL) to an altitude of 12,000 feet MSL was less below 8500 feet MSL than the average values for such nuclei distributions as found by Wigand, Landsberg, and Weickmann. The average Aitken "background" count/cm^3 at Fort Collins remained constant or increased slightly with height above 8500 feet MSL unlike the results found in the other mean soundings. This limited sampled indicates that the air in the vicinity of Fort Collins may be slightly "cleaner" below 8500 feet with regard to total number of Aitken nuclei than other areas of continental air that were used in the comparisons. Above 8500 feet, the total number of Aitken nuclei is still slightly less than the other average values studied.

RECOMMENDATIONS FOR FURTHER STUDY

The results obtained herein suggest that the continential air masses over Fort Collins may be somewhat deficient in Aitken nuclei counts as compared to other continental areas. However, this result is based on a rather limited sample. Further sampling should be initiated so that more positive conclusions could be made. Then these more positive conclusions may shed some new light on the possibly differing cloud characteristics of this region. The correlation between the vertical distribution of Aitken nuclei background concentrations and the occurrence of hail in northeastern Colorado may also be worthwhile investigating.

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