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Measurements to Evaluate the Benchmark Properties of Atmospheric Aerosols

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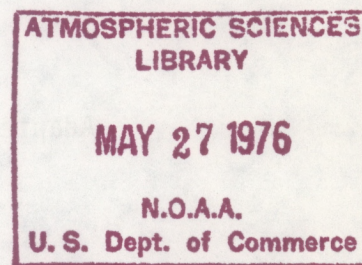Robert M. White, Administrator
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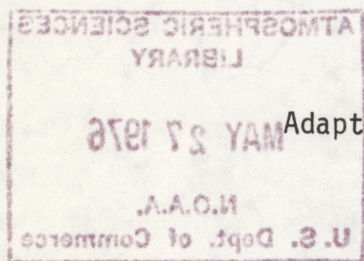
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PROPERTIES OF ATMOSPHERIC AEROSOLS

Bernard G. Mendonça

ABSTRACT

An experimental program was designed to monitor and analyze
atmospheric aerosols. Observations from two Fort Collins sites
indicate that the urban signature in aerosol concentrations, size
distributions, hygroscopicity, and organic content is evident to
≃5.0 km from the center of the city. The surface sampling in this
study showed the mass median diameters of the aerosol measured to
be in the 2.5×10^{-4} cm range. The submicron aerosols, however,
were the more hygroscopic, the more active cloud condensation nu-
clei, and were slightly more organic in content. Evaluation of
the instruments and techniques used describes the shortcomings of
the measurement system, as well as the benefits of a composite
measurement array for benchmark monitoring of atmospheric aerosols.

1.   INTRODUCTION

Perhaps the first realization of a global scale intrusion of aerosol in-
to the atmosphere in historic times occurred after the Krakatoa eruption of
1883 (Lamb, 1970). Since then the awareness of atmospheric aerosols and
their implications has grown in proportion to man's technology and industrial
activity. In 1947 Langmuir's experiments (Langmuir and Schaefer, 1947, 1952)
with artificial ice nuclei to form supercooled clouds described the manipu-
lative effect that aerosols could have in cloud ice crystal formation. At
the same time the consequences of atom bomb explosions forewarned of the
drastic consequences that radioactive particles could have on a global scale.
More recently the health hazards of atmospheric aerosols have come under
scrutiny. The Surgeon General's report on cigarette smoke and the effect
that polluted industrial environments have on health attest to the hazards
involved in suspended particle inhalations. Recent investigations have
attributed to atmospheric aerosols secular decreases in direct solar energy
incident on the Earth (Ellis and Pueschel, 1971; Flowers et al., 1969).

Conversely, artificial ice nucleus particles judiciously applied to the
atmosphere are being used by man to augment meager rainfall over sizeable
areas. Aerosols applied to the atmosphere are also being used to disperse
fogs over airports and to prevent severe hail storms and lightning. There
is even speculation about dissipating hurricanes with carbon black seeding.

Because atmospheric aerosols can participate in the microphysics of
weather, because on a local scale they can pose potential human health ha-
zards, and because on a broader scale they may affect the heating and cooling
of the Earth, atmospheric aerosol research is currently an active field of
study.

In order to complement such investigations as well as to learn of any large scale effects attributable to atmospheric aerosols it is imperative to monitor and describe the background aerosol of the atmosphere. Particular emphasis should be on current levels, secular trends, and changes in chemical composition and physical make-up of atmospheric aerosols.

The intent of this study was to select several suitable aerosol parameters for measurement and monitoring of the benchmark properties, and to execute some "benchmark" aerosol monitoring with the utilization of air pollution instrumentation, techniques, and viewpoints.

This study suffered the constraints of limited time and funding. It was restricted to a land-based utilization of present and available instrumentation and techniques. Furthermore, durable instrumentation which provided for repeatability in measurements was favored for long term observations and analysis. Simplicity of operation was also favored for general use with minimum training. Accuracy and sensitivity of measurements were important in this study; however, the availability of instrumentation was the primary limiting factor.

2. SOURCES

In any attempt to assess the background atmospheric aerosol, major sources and sinks must be considered. Of the total global burden to date, only 10% of the atmospheric aerosol is of anthropogenic origin. But it is also true that in selected regions and over limited time frames, an overburden of many times the global average of the anthropogenic contribution exists, as in the urban and industrial zones of the eastern U. S. and central Europe. Further, with the best estimates of future global industrial and population growth, it seems plausible that this 10% figure will increase. Nonetheless, natural sources are dominant on a world-wide basis. These sources are basically confined to the surface of the Earth. Those most commonly carried aloft from the Earth's land surfaces are dust and sand. The transport process is maintained by weathering, wind action, and atmospheric convection. Sea salts are another universal global aerosol. Bursting of bubbles on the surface of the seas provides a continuous supply of particulates to the atmosphere. A natural organic component of total global aerosol is formed by the emission of hydrocarbon compounds from vegetation. In the presence of sunlight these volatile molecules react photochemically to generate clouds of aerosols (the blue haze over forests) with particle diameters usually less than 0.2×10^{-4} cm.

Another fractional component of the global aerosol consists of aerosols having less uniformity in distribution, but more diversity in composition. These are the products of combustion and subsequent gas particle conversions, both natural and industrial. Forest fires and fossil fuel burning are known to produce great quantities of fine particulate matter. Furthermore, high supersaturations caused by quenching of combustion vapors permit gas-to-particle conversions. Like the natural organic component this process produces particles with diameters originally $\leq 0.2 \times 10^{-4}$ cm. In polluted urban areas

the gaseous and fine particulate products of combustion in the presence of hydrocarbons, NO_2, and sunlight can undergo further gas-to-particle conversion and provide still another source of atmospheric aerosol (the notorious L. A. smog). Other very localized, but possibly intense, sources of atmospheric aerosol are volcanoes. Big eruptions can eject enough to contaminate large portions of the troposphere as well as the lower stratosphere where the aerosols can persist for years.

Finally, radioactive processes and intrusions of extra-terrestrial material contribute to a small portion of the global burden. The former are very pertinent when they introduce radioactive wastes with possible lethal effects. Excluded from the atmospheric aerosol burden have been the obvious and always present hydrometeors that make up the clouds and precipitation components with which we are not concerned in this report.

3. CONCENTRATIONS AND SIZE DISTRIBUTIONS

The first inroads in assessing the benchmark characteristics of atmospheric aerosol have been measurements of particulate concentrations and size spectra. The "aerosol size" most commonly used in these measurements is defined as the effective aerodynamic volume that the aerosol particle would have if it were a solid sphere of density-1 moving in air. This size is expressed as the diameter of the sphere. Concentrations and size spectra have been observed that span the range from $\simeq 200$ particles/cm^3 in clean air to $\simeq 10^7$ particles/cm^3 in polluted urban areas and sizes ranging from individual ions to particles $\simeq 10 \times 10^{-4}$ cm near the surface (Junge, 1955). Particles larger than 10×10^{-4} cm are usually not observed except very near their sources because their fall velocities ($\simeq .033$ m/s) prevent long residence times in the atmosphere. Apart from the variations close to the surface, aerosol concentrations normally experience a decrease with height or distance from the source (Junge, 1961; Weickmann, 1957).

Junge (1968) has shown that continental aerosols follow a power law size distribution that varies little despite considerable differences in the mean aerosol concentrations from one locality to another as well as fluctuations in concentrations due to meteorological influences (fig. 1). This law is expressed as

$$\frac{dN(r)}{dr} = 0.434 \ C \ r^{-(B+1)} \ , \tag{1}$$

where N(r) = number of particles per unit volume belonging

to the radius range of r ± dr,

r = radius of the particles,

c = constant with a range between 1 (high mountains) and 10 (low lands) and units of cm^3 if r is expressed in 10^{-4} cm, and
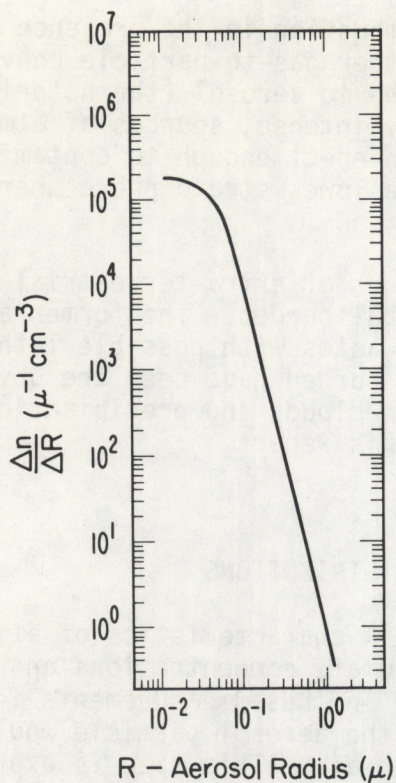
B = an exponent describing the power law distribution.

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Figure 1. *Junge's European-continental aerosol size distribution. The number density of aerosols per unit range of particle radius Δn/ΔR is plotted against aerosol radius. In this case the slope of the curve (β) from $R = 8 \times 10^{-2}$ to $R = 8 \times 10^{0} \mu$ is very close to 4.*

The observation of Junge's distribution is explained on the premise that Brownian motion permits collisions and coagulation of particles. Then with increasing size the larger ones undergo gravitational settling. There must also be a continuing supply of smaller particles ($\leq 0.1 \times 10^{-4}$ cm) to continue the distribution over long periods of time.

Other distributions have been observed, but they differ mainly in that the original distribution lacked a significant number of the smaller size particles and the range of maximum frequency is shifted toward larger radii. Distributions near sources can also differ and exhibit several peaks corresponding to the predominant particle sizes emitted. Other effects can also prevent attainment of the Junge distribution as when surface-active chemicals such as fatty acids and alcohols in urban pollution alter coagulation kinetics by stabilizing large particles and impeding their growth (Gitchell et al., 1974; Hobbs et al., 1974). Recently, studies have also shown significant anomalies in the normal decrease in aerosol concentrations with height over the equatorial Atlantic (Carlson et al., 1973; Prospero and Carlson, 1972). Special meteorological conditions of drought, wind storms, and dry convection over North Africa have carried dusts aloft which resulted in transport over the Atlantic to the Caribbean Sea.

An application of the Junge distribution in which there is particular interest is the obtaining of the relationship for the mass distribution of the aerosol from equation (1). By assuming spherical particles and a suitable particle density and multiplying both sides of the equation by the volume,

an expression for the mass distribution of the aerosol can be obtained,

$$\frac{dM}{d(\log R)} = \frac{4}{3} \pi \rho r^3 r^{-\beta} 0.434 \, C \quad .$$

Junge has found the exponent β to have a value of $\simeq 3$ within the particle size ranges of 0.1 to 1.0 x 10^{-4} cm in which case equation (2) reduces to

$$\frac{dM}{d(\log R)} = \pi \rho \, 0.5787 \, C \quad ,$$

and the mass distribution in relation to the total mass of the aerosol for each particle size range is comparable with any other.

Besides the collision and coagulation processes described by Junge, climatological and meteorological parameters influence atmospheric aerosol concentrations as well as size distributions. Turbulence associated with weather phenomena helps to disperse aerosols vertically and horizontally. Deposition by impaction of particles is also enhanced through turbulent exchange. Temperature inversions can alter vertical gradients and provide for intense concentrations aloft. But most important are the precipitation processes of rainout and washout. The first is most important in the removal of aerosols (≤ 1.01 x 10^{-4} cm) by diffusion and the larger sizes by nucleation processes. Washout is more effective in removing the larger particles by collision and coalescence.

4. THE EFFECTS

When the benchmark properties of atmospheric aerosol are being evaluated, effects on the environment and its inhabitants must be considered. Three major concerns in the monitoring of atmospheric aerosols are their behavior in nucleation processes, their role in the radiation budget, and their toxicity to living organisms.

4.1 Nucleation

Atmospheric aerosols can function as either ice nuclei or cloud condensation nuclei (CCN) in the natural atmospheric precipitation processes. As such they are an initial ingredient necessary to the atmospheric loop in the hydrological cycle that maintains life on Earth. The condensation process of water vapor on a curved surface (aerosol) was first described by Thomson (1888). Later modifications on Thomson's equation to include electrical effects and hygroscopic droplets were developed. Since then the unique function of atmospheric aerosols as nuclei in the atmospheric condensation processes has related to the temperature of activation, to the composition, shape, charge, and size of the particle, and to the atmospheric water vapor supersaturation. Consequently, in evaluating the benchmark qualities of atmospheric aerosols, the portion that acts as nuclei as well as the conditions of activation should be assessed.

4.2 Radiation

Atmospheric aerosols absorb and scatter solar radiation in the atmosphere. Because of this, they are capable of redistributing energy fluxes, attenuating direct incoming radiation, and acting as heat sinks and sources in the atmosphere. Keeling et al. (1975) suggest that an aerosol burden of about 10^{-8} kg m^{-3} of air can produce a heating rate corresponding to 0.5°C per 12-hour day. In urban areas a heating rate may exceed 1.0°C per hour, although this neglects multiple scattering. On the other hand, atmospheric aerosols at concentrations less than 10^{-6} kg m^{-3} appear unable to contribute significantly, in comparison with H_2O vapor and CO_2, to cooling of air. In the size ranges most frequently observed, scattering of the visible and near ultraviolet light is the dominant radiative effect of atmospheric aerosol (Mitchell and Murray, 1971).

4.3 Health

Potentially the most serious and immediate effect of atmospheric aerosols is in its toxicity to living organisms. The effluents of industrial activity are particularly conducive to producing aerosols that cause eye irritation and damage to the respiratory systems of humans. The synergistic effect of the oxidation of gaseous SO_2 in the presence of water vapor to form particles and its caustic consequences after inhalation into the lungs; silicosis due to exposure to high concentrations of free silica particles; asbestosis from inhalations of asbestos fibers; and anthracosis from the inhalations of coal dust are all specific examples of ill effects caused by aerosol inhalations.

The severity of any adverse effects of aerosols depends on length of exposure, the ambient concentrations, and the size of the individual particles as well as the composition of the aerosol. Most ill effects have been traced to excessive ambient concentrations, while the long range effects of prolonged exposure at lesser concentrations are still largely undetermined. Generally particles larger than 7×10^{-4} cm fail to penetrate beyond the pharynx; particles smaller than 0.4×10^{-4} cm are inhaled and exhaled with little or no deposition (Williamson, 1973). Other ill effects such as radioactive poisoning, crop damage, and allergic reactions can also result from aerosols.

5. THE PARAMETERS CHOSEN FOR MEASUREMENTS

In this study, aerosol number concentrations were chosen because of the wealth of past observations that are available for long term change analysis. The potential for climate change and the danger of exposure to aerosols are first based on aerosol concentrations. The maximum concentrations observed in urban pollution have shown measurable effects on nucleation, radiation, and health.

In conjunction with aerosol number concentrations the total mass equivalent was also selected for measurement. Cross analysis between concentrations and mass equivalent facilitated an indepth classification of the aerosol. Monitoring at air pollutions sites has used the mass equivalent as an inexpensive and repeatable measurement of atmospheric aerosol. Its utilization together with the more standard meteorological techniques of measuring aerosols can provide a link up between the two methodologies.

Next to the number concentrations the size distributions of atmospheric aerosol determine the extent of its effect in nucleation, radiation, and health. Simple aerosol size determinations were made to reinforce the aerosol classifications. Two more parameters were chosen, the hygroscopic tendency and organic component of the aerosol, in an attempt to specify the chemical content of the aerosol.

6. INSTRUMENTATION AND TECHNIQUES

6.1 Concentrations

To measure concentrations, a portable battery-powered and hand-operated Gardner Associates small-particle detector was used. It operates on an expansion-cooling principle to nucleate and grow suspended water particles at supersaturations exceeding 200%. Detection is by measuring light attenuation scattering by a photometric technique. The basic instrument known as a condensation nucleus counter, is explained by Rich (1955).

The calibrated range of this instrument is from 200 n/cm^3 but is most accurate over the ranges 10^3 n/cm^3 to 150,000 n/cm^3. One observation takes 30 to 60 seconds and detects nuclei with radii from 10^{-7} to $\simeq 10^{-3}$ cm. Particles with radii greater than 10^{-3} cm are lost, either in the intake line of the internal plumbing of the condensation nucleus counter by impaction, or settling before they get to the expansion chamber. Particles with radii less than 10^{-7} cm are generally below the critical radius for supersaturation in the instrument and therefore do not act as nucleating particles. The instrument used was compared with the resident condensation nucleus counter at the Simulation Laboratory at Colorado State University (CSU) throughout the study.

In conjunction with the above instrument an automatic cloud condensation nucleus (CCN) counter independently determined CCN concentrations. The counter uses a parallel plate thermal diffusion chamber to obtain supersaturations from 100% to 104%. CCN were activated and counted by photometric detection of light scattered at a 45° angle. Observations were taken and visual calibrations were periodically made throughout the study. For a general description of this instrument consult the manual of the Model 30 CCN counter, M.E.E. Industries. The nuclei measured with this instrument ranged between 0.01 x 10^{-4} cm to $\simeq 1.0$ x 10^{-3} cm diameter particles. The CCN counter has a resolution of 20-second intervals and gave in-situ measurements of aerosol populations during the study.

6.2 Mass Equivalent

To determine the mass equivalent of aerosols, Gelman Hi-Vol air samplers drew air through filter substrates which collected particles, either by impaction, diffusion, or filtration. The high volume air samplers used a centrifugal, constant-volume type pump, completely isolated from the motor to prevent contamination. and measured air flow by the orifice plate principle directly on a pressure gauge (Lee and Goranson, 1972). The samplers accomodated 8 x 10 inch retangular filter holders. Air flow was corrected for ambient temperature (T) and pressure (P) by the relationship

$$\text{SCFM} = \text{Measured CFM} \sqrt{\frac{P \text{ discharge}}{P \text{ calibrate}} \times \frac{T \text{ calibrate}}{T \text{ discharge}}} \, ,$$

where SCFM = standard cubic feet per minute.

A typical correction factor during the sampling was ±1.01.

Filters were mounted on the air samplers to collect aerosols. The final choice of filter weighed heavily on the maximum flow rate ratings in anticipation of large volume requirements at clean-air sites. Consequently, nonhygroscopic, binderless glass-fiber filters (flow rate 60 liters min^{-1} cm^{-2}) were selected (Gelman Type A). A bonus with this filter was its general and long use in urban sampling where back data already exist (Williamson, 1973). Circular glass-fiber filters of the same type were also used to impact aerosols in determining size distributions.

6.3 Size Spectra

Forty-seven mm diameter Nuclepore filters were used for spot sizing of aerosols during the study. They were used in preference to fibrous filters because, in contrast to fibrous filters, these are made with a 1.0 x 10^{-3} cm thickness monofilm substrate perforated with uniform pore sizes which offer effective direct physical barriers for the larger-than-pore-size aerosols (Melo and Phillips, 1974). Particular care was taken, by way of short sampling periods with low flow rates, to prevent overloading of the filters which could modify sizing during the observations. The filters were placed upstream on the Gardner counter and CCN counter intakes.

Large volume sizing was done with a high volume cascade impactor. Initially a BGI Incorporated high volume cascade impactor was used (Gussman, 1972), but because of the small impact surface areas and dry ambient sampling conditions, the receiving surfaces reached saturation, and particle bounce-off occurred before an adequate aerosol sample could be collected. This unit was replaced with an Anderson Hi-Vol head impactor which fitted on the Gelman Hi-Vol sampler. It fractionalized the aerosol according to equivalent aerodynamic 50% cutoff diameters of 7.0, 3.3, 2.0, and 1.1 x 10^{-4} cm at 20 SCFM air flow. A glass-fiber backup filter was used to collect

submicron particles. This instrument provided a bigger impact area and permitted an adequate sample for analysis. The operational principles of the instrument are explained by Burton (1972). The effective cutoff diameter (ECD) for each stage is determined by a dimensionless parameter T (Meicer, 1964, and Ranz and Wong, 1952), where

$$T^{\frac{1}{2}} = \left(\frac{V_j \; \rho \; CD_p^{\;2}}{18 \; \eta \; D_j} \right)^{\frac{1}{2}} \tag{5}$$

and where V_j is the jet velocity,

                 ρ is the particle density,

                 C is the Cunningham correction factor,

                 η is the viscosity of the air,

                 D_j is the diameter of the jet, and

                 D_p is the diameter of the aerosol particle.

Where there is little variation from the 20 SCFM calibrated air flow, the ECD can be adjusted by using the relationship

$$\text{ECD (I)} \; = \; \frac{K(I)}{R} \; ,$$

where   K = a constant related to stage I,

                 I = the impactor stages--ranged from 1 to 4, and

                 R = the air flow rate.

Then the ECD(I) = effective cut of diameter for stage I.

This relationship was used when a $\geq$ 10% departure from 20 SCFM persisted during the observation.

6.4 Organic Fraction

An organic fraction of the aerosol was obtained using a Soxhlet extraction method. Reagent or spectroscopic grade benzene (solvent strength ε = 0.32)* was used as the solvent because of its known effectiveness and its widespread use in past studies (Gordon, 1974). Filter samples were extracted for 4 hours with an average of 5 extractions per hour. Under such tedious extractions up to 99% of the organic fraction can be removed from the

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* The solvent strength is defined as the distribution coefficient of solute between the solvent and a standard solid absorbent (in this case, alumina) in liquid-solid absorption chromatography where ε = solute dissolved in benzene/ total solute added (Snyder, 1968).

aerosol sample. Blanks were processed throughout the extractions to provide background estimates. They averaged 1.2 mg with σ = 0.48 mg. Only the total benzene soluble fraction was determined. This fraction should include most of the polynuclear aromatic hydrocarbons (PAH) which are taken out by solvents with $\varepsilon \simeq 0.3$. Solvents with $\varepsilon > 0.3$ extract large amounts of highly polar organics but they also dissolve some of the more soluble inorganics. Fractionation of the total organic component measured into its constituents was left for further studies, even though some (PAH) have been shown to be active in particle generation and others (alcohols, fats) active in inhibiting coagulation (Stern, 1968).

6.5 Hygroscopic Tendency

The aerosols collected on filters were tested for hygroscopicity by being exposed in a glove box to different humidities. Humidities were maintained by aspirating the glove box air over saturated solutions of $NaNO_3$ (73.8%), NH_4Cl (79.3%), KNO_3 (92.5%), and $K_2Cr_2O_7$ (98.0%). A 24-hour period was long-enough to insure saturation at all humidities.

Weight gain due to moisture absorption was determined after each exposure. Blank filters again were used throughout the analysis to provide internal checks. They averaged 4.5 mg and σ = 1.3 mg. The technique provided a measure of the amount and rate of moisture pickup by the aerosols under simulated atmospheric humidities. An extraction technique to determine the water-soluble fraction similar to that for the organic analysis proved unworkable with glass-fiber filters. With distilled water as a solvent the temperature of extraction caused water-leaching of sodium nitrates from the filters to result in intolerable blanks (Holland, 1968).

6.6 Mass Determinations

Gravimetric measurements were used for all mass analyses in this study. A Mettler balance with a readout accuracy down to 10^{-5} g was used. All filters were preconditioned and weighed before and after exposure under similar conditions at relative humidities of 30% to 40%, where moisture pickup is minimum. Extractions were handled carefully, and care was taken to prevent contamination and insure temperature equilibrium before all weighings. The balance was compared with calibration weights and with a Cahn electrobalance. Weighting accuracies to 0.5 mg were repeated consistently.

6.7 Observation Sites

Measurements were made on 34 days at two sites in Fort Collins, Colorado. All sampling instruments were housed in a wooden shelter 1.2 m above the surface. Site A at the base of the wind tower in the open field adjacent to the CSU Simulation Laboratory was used for all preliminary observations. Site B was situated on the grounds of the CSU athletic field adjacent to College Avenue and Old Main Drive. This downtown site is $\simeq 5.0$ km SW of Site A at the foothills campus. Both sites were used for aerosol monitoring.

Instrument placement exposure and operation were uniform at both observation sites. The Appendix summarizes the instruments used and the measurements taken. A schematic flow of the measurements is also given (fig. A.1).

7. RESULTS

7.1 Concentrations

Concentrations of condensation nuclei at both sites ranged from an afternoon maximum of $1.5 \times 10^5 \text{cm}^{-3}$ at site B to a night-time minimum of $1.5 \times 10^3 \text{cm}^{-3}$ at site A. Even though a continuous 24-hour data sample is lacking, the spot sampling (figs. 2 and 3) shows a diurnal variation (daytime maximum)
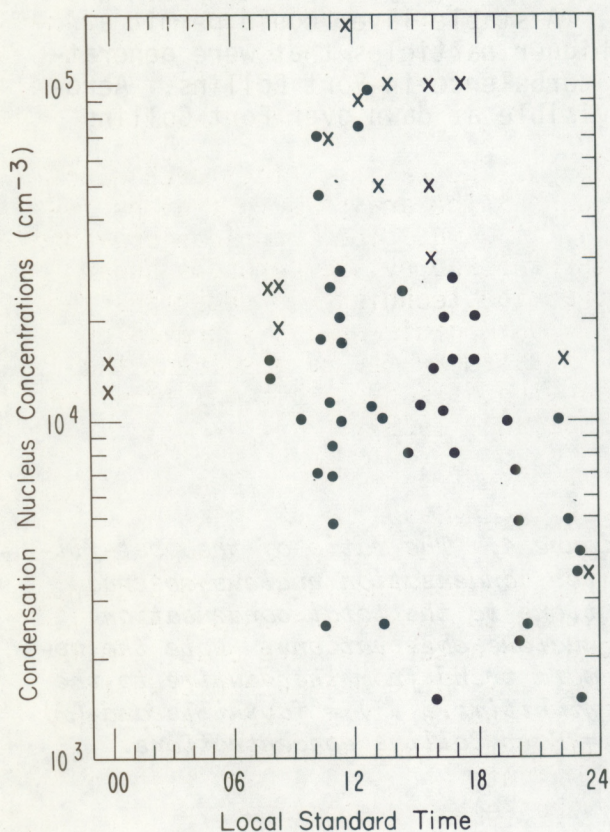
Figure 2. *Plot of diurnal condensation nucleus concentrations. Foothills concentrations (·) are lower than the downtown Fort Collins (x) concentrations, but both show a daytime maximum.*
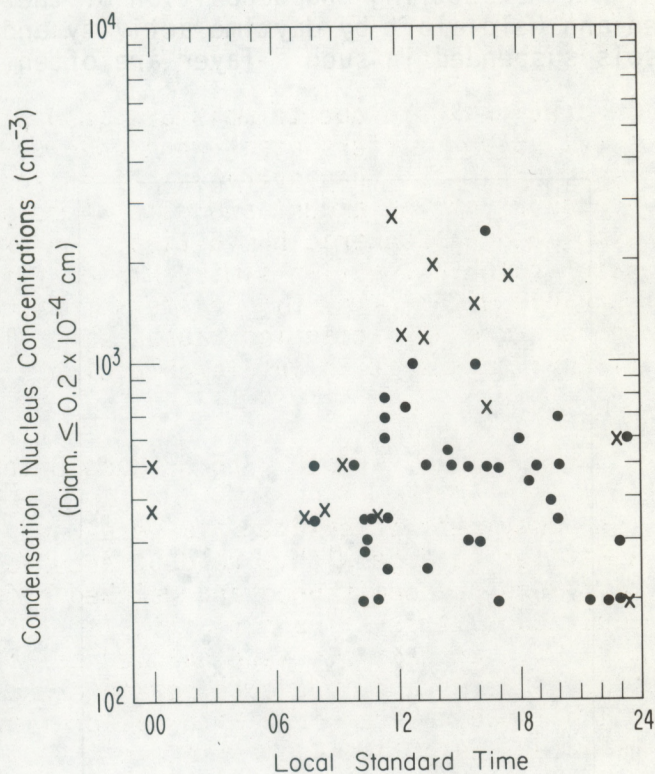
Figure 3. *Plot of diurnal condensation nucleus concentrations measured after ambient air is filtered through a high volume glass fiber filter. The trend is the same as the total concentrations. (·) = foothills and (x) = Fort Collins concentrations.*

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with wide scatter in aerosol concentrations at both sites. Both the magnitude and scatter agree well with Israel and Israel's (1974) reports of aerosol concentrations in urban and adjacent areas. Aerosol concentrations at site A had a wider range then concentrations at site B. This was because site A was sometimes upwind and sometimes downwind from Fort Collins where urban activity produced a high aerosol generation. Generally, upwind conditions reduced the concentrations and diurnal maximum at site A.

Both the total (unfiltered air) and post-filter (filtered air) concentrations (figs. 2 and 3) show maximum generations during the daytime because of human and vehicle activity, possible photochemical generations, and a more turbulent boundary layer; however, the concentration ratios of smaller aerosols to the larger show a daytime minimum (fig. 4). Aerosols $> 10^{-4}$ cm in diameter composed more than 60% of the total concentrations measured. Greater attrition rates of these $> 10^{-4}$ cm diameter aerosols during the period of nocturnal cooling and formation of a stable surface layer could explain the nighttime maximum in concentration ratios. A stable layer could permit a nighttime settling and deposition of the bigger particles that were generated and held aloft by daytime activity and turbulence in Fort Collins. Aerosols suspended in such a layer are often visible at dawn over Fort Collins
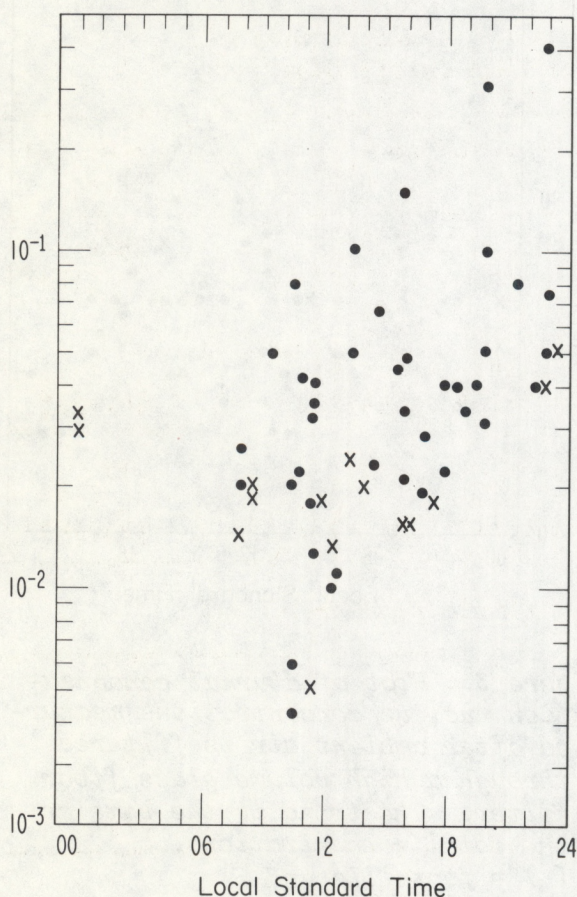

Figure 4. The ratio of the post-filter condensation nucleus observations to the total condensation nucleus observations. Note the upward trend from the daytime to the nighttime. (·) = foothills and (x) = Fort Collins concentrations.

after clear nights. The nocturnal reduction to a lesser degree of submicron aerosols would not be mainly by sedimentation, but by coagulation processes. From these observations, the urban signature in aerosol concentrations and distributions is very visible in the surface layer to at least 5.0 km away from the urban center.

An attempt was made to monitor the change in aerosol concentrations of the filtered air with duration of exposure. The intent was to determine if the coefficient of filtration of submicron aerosol would increase significantly with exposure time and aerosol accumulation. Independent checks with Nuclepore filters showed that the difference as detected by the Gardner counter in post filter (submicron) concentrations was more dependent on the ambient concentrations than on the duration of the glass-fiber filter exposure in the majority of cases.

7.2 Size Distribution

Observations of aerosol concentrations of both condensation nuclei (CN) and CCN were made at both sites. Table 1 contains the averages from both sites.

Table 1. Condensation Nuclei – Sites A & B Combined
Average Concentrations (cm^{-3}) Less Than Cutoff Diameters

Type	Total Ambient	Cutoff diameters x 10^{-4} cm				After Hi-Vol Filter
		8.0	1.0	0.5	0.2	
CN	21,900 (18)	15430 (5)	1925 (5)	885 (8)	276 (8)	398 (18)
CCN (0.1% SS) Range	1069 (17) 1916-503	744 (5) 942-583	517 (8) 728-313	316 (8) 497-204	306 (8) 354-200	296 (12) 447-222
CCN (0.1% SS) Range	430 (18) 637-220	439 (5) 584-352	344 (8) 507-260	294 (8) 431-219	279 (8) 358-187	219 (12) 300-167

Percent of Nuclei Less Than Particle Diameters

CN		71	09	04	01	02
CCN (0.1% SS)		70	48	30	29	28
CCN (0.1% SS)		100	80	68	65	51

Numbers in parentheses are numbers of observations.

CCN measurements were made at supersaturations of 1.1 and 1.01. The size of the particles passing through the Hi-Vol filters lies between the 0.5×10^{-4} cm and 0.2×10^{-4} cm diameter range for the CN, and at the 0.2×10^{-4} cm range for the CCN observations. While virtually all (98.2%) of the CN were effectively filtered out by the Hi-Vol filters, this was not so for the CCN where 28% and 51% at 1.0% and 0.1% supersaturations respectively got by the high volume filters. The result is evident in figure 5 where a converging of populations of CCN and CN is seen down in the 0.2×10^{-4} cm range. This stratification occurred at both sites and the observations define the CCN particles as those predominantly in the Aitken range rather than in the more populous bigger sizes observed in this study.

Sizings below 0.2×10^{-4} cm were not obtained because of the difficulty in drawing air through the smaller pore sizes of the Nuclepore filters. Such attempts created a partial vacuum in the thermal diffusion chamber of the CCN counter.

From the concentrations and size distribution sampling of the CN concentrations the range of $10^4 n/cm^3$ was common, but biased toward $> 1.0 \times 10^{-4}$ cm diameter particles. Conversely CCN concentrations of 500 to 1000 were observed, but biased to the $< 0.2 \times 10^{-4}$ cm diameter particles.
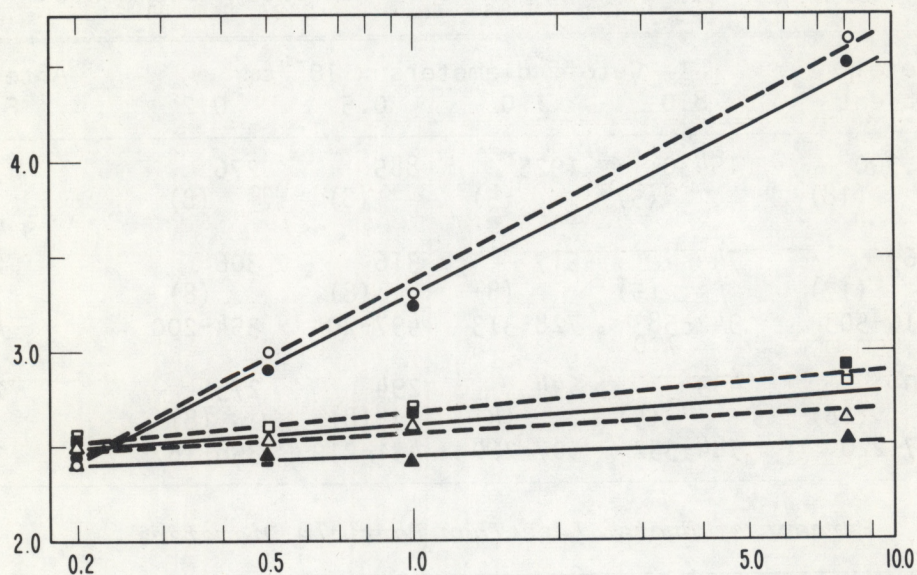
Figure 5. Plot of the log of the ambient aerosol concentrations in relation to the aerosol diameter. o = condensation nucleus concentration, □ = cloud condensation nucleus concentrations at 1.1 supersaturations and Δ = cloud condensation nucleus concentrations at 1.01 supersaturations. Open symbols are for foothills data; solid symbols are for Fort Collins data. All the concentrations converge to the smaller aerosol sizes.

7.3 Mass Equivalent

A summary of the aerosol mass equivalent collected on the stages of the Hi-Vol cascade sampler is shown in Table 2. The total collected was five times greater at site B (downtown Fort Collins) than at site A (foothills). However, the proportions of the total on each stage were nearly identical. The range at site B was greater. At both sites the bias toward the larger particles as in the concentration sampling is clearly evident, where more than 50% of the aerosol mass is collected on the first two stages. There was good agreement between the total aerosol collected on the high volume sampler and the total of all the stages on the cascade impactor at both sites.

A plot of the mass distribution by aerosol size according to the technique described in the report of the cascade impactor network by the Environmental Protection Agency (Lee and Goranson, 1972) is shown in figure 6. The cumulative percent mass is determined by

$$CPM\ (I)\ =\ \frac{Cum\ wt\ (I)\ x\ 100}{Cum\ wt\ (5)}\ , \tag{7}$$

where (I) is the stage of the impactor and (5) is the cumulative weight of all the stages, including that of the backup filter. The plot in figure 6 is then 100-CPM (I) or the cumulative percent mass less than or equal to the cutoff diameter of the stages of the impactor. If the particle sizes of the aerosol are nearly log-normally distributed then the mass median diameters

Table 2. Average Aerosol Mass Equivalent Collected

	Total Mass μgm m^{-3}	Percent of total mass on impactor stages Cutoff diameters (x 10^{-4} cm)				
		7.0	3.3	2.0	1.1	Hi-Vol Filter
CSU Avg.	143.4	43.1	15.2	7.8	8.7	25.8
Range	92.5 to 192.2					
Sim Lab Avg.	38.7	35.7	14.9	11.5	10.0	27.9
Range	76.7 to 24.9					
Combined		39.4	15.0	9.6	9.3	26.8

Ratio $= \dfrac{\text{total mass collected} \quad\quad\quad\quad \text{Hi-Vol}}{\text{total mass collected} \quad \text{Anderson stages and backup filter}}$

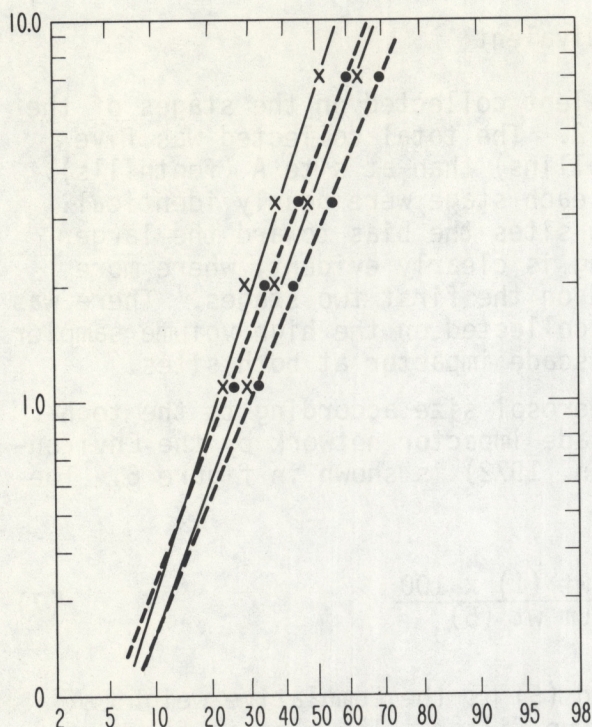Sim Lab Ratio = 1.4

CSU Ratio = 1.03

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Figure 6. The mass distribution of the aerosol according to particle diameter, assuming a log normal distribution. The mass median diameters are indicated. (•) = foothills and (x) = Fort Collins.

are found at the 50% mass cumulative point. Assuming this, the mass median diameters all lie above 2.0×10^{-4} cm and show wide variation, but the slopes of the distributions are all similar. Of the two runs plotted for both sites in figure 6, one was taken before a pronounced cold front traversed Fort Collins on July 22, 1973, and the other after the frontal passage. At both sites there is a drastic drop in the mass median diameter after the frontal passage, but on change in the slope of distribution. This shift in the mass median diameter could identify two different air masses. More observations are needed to confirm such changes across a frontal system.

These mass distributions resemble others observed in urban areas where wider variations in mass median diameters as well as slopes are the rule, rather than the exception. The mass distributions obtained from this study are similar to those obtained by Whitby and Husar (1971) in Fort Collins. They found 10% or less of the mass was usually associated with aerosols with diameters below 10^{-4} cm. In this study, about 20% was below 10^{-4} cm diameter aerosols.

7.4 Hygroscopic Tendency

The determination of the hygroscopic tendency of the atmospheric aerosol was used to simulate the behavior of the aerosol at subsaturation conditions. The ability of an aerosol to absorb moisture can alter its original size and spectrum as well as its scattering properties. Measurements of moisture absorption were made across the range from 40% to 98% relative humidity. Table 3 summarizes the results from several samples. Generally, the hygroscopicity of the aerosol increases toward the submicron aerosol. The ability of the aerosol to absorb moisture improves with a decrease in

Table 3. Aerosol Absorption of H_2O;
Composite of Sites A and B

Aerosol size greater than x 10^{-4}cm	$\dfrac{\text{mass } H_2O}{\text{mass aerosol}}$	RH intercept	$\dfrac{\text{slope } \left(\dfrac{dmH_2O}{dRH}\right)}{\text{mass aerosol}}$
7.0	0.25	73.1	0.098
3.3	0.40	73.3	0.167
2.0	0.30	72.0	0.107
1.1	0.76	73.6	0.306
0.2	0.67	66.8	0.259

Relative humidity range: 40% to 98%

diameter. When the amount of moisture pickup for each size range was computed for different humidities and fitted to a least square straight line fit distribution, the relative humidity intercepts showed a 7% separation between the submicron aerosol and the larger diameters. This shift to lower humidities of the onset of absorption for the submicron aerosol is attributed to a difference in chemical species between the submicron aerosols and the larger aerosols.

The rate of moisture pickup as a function of relative humidity is also an identifying factor of the aerosol. This deliquescence, the slope of the above straight line fits, normalized by dividing through by the aerosol mass for each stage, is plotted against particle diameter in figures 7 and 8. The similarities and change in this parameter at both sites before and after the frontal passage again suggests a basic change in aerosol content with the frontal passage. The change in rate for the 1.1 x 10^{-4} cm diameter aerosol range is the most dramatic, being very active before the frontal passage and least active after.

7.5 Organic Fraction

The organic fractions determined by the benzene extraction technique suffered from inconsistencies when the organic portions collected on the impactor stages approached the limits of detectability. The average fraction was ≈ 6.5% of the total aerosol collected at both sites. However, the sum of the components for the impactor stages was a factor of 1.5, the amount of all the aerosol collected on a single high volume filter. This was attributed to a drying problem when the concentrations of the solute increased toward the end of the benzene evaporation. The evaporation vapor pressure of the benzene decreases according to Raoult's Law and proper drying becomes difficult and may require longer times than those applied in this analysis. Accordingly the impactor stage amounts were adjusted to the fraction of the
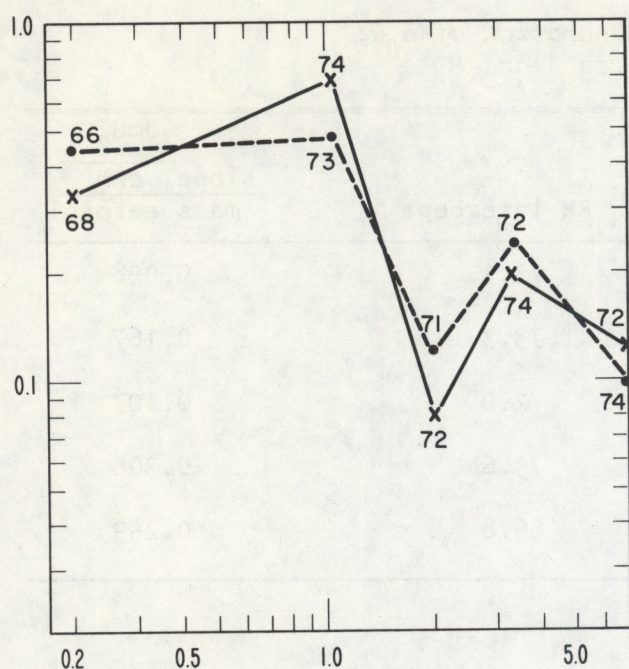
Figure 7. The rate of moisture accumulation on the aerosol as a function of the ambient relative humidity before frontal passage.
$d\,m_{H_2O}/dRH = slope\ per\ gram\ aerosol.$

The relative humidity intercepts of where moisture pickup begins are indicated: (•) = foothills and (x) is Fort Collins.
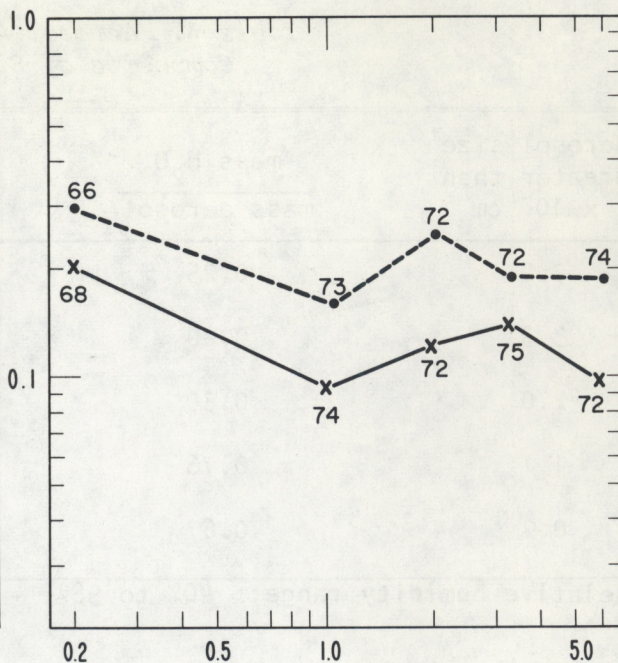
Figure 8. The rate of moisture accumulation on the aerosol as a function of the ambient relative humidity after frontal passage.

high volume samplers. In the analysis of the small aerosol masses collected on stages 3 and 4 of the impactor, the tolerance of the background levels of the analysis technique was reached. Consequently the organic portions determined for these stages are questionable. In the first and last stages however the data showed valid results. All the data are presented in figure 9. The percent of the total mass that is organic is plotted against each stage. The submicron aerosol has the higher organic portion particularly with regard to the first stage where there was sufficient aerosol of the larger diameters to make the analysis more dependable. Again a change is discernible from a higher prefront amount to a lesser amount after the frontal passage. The amounts of the organic portions for the total aerosol analysis agree well with data results from Denver as well as other Rocky Mountain areas.
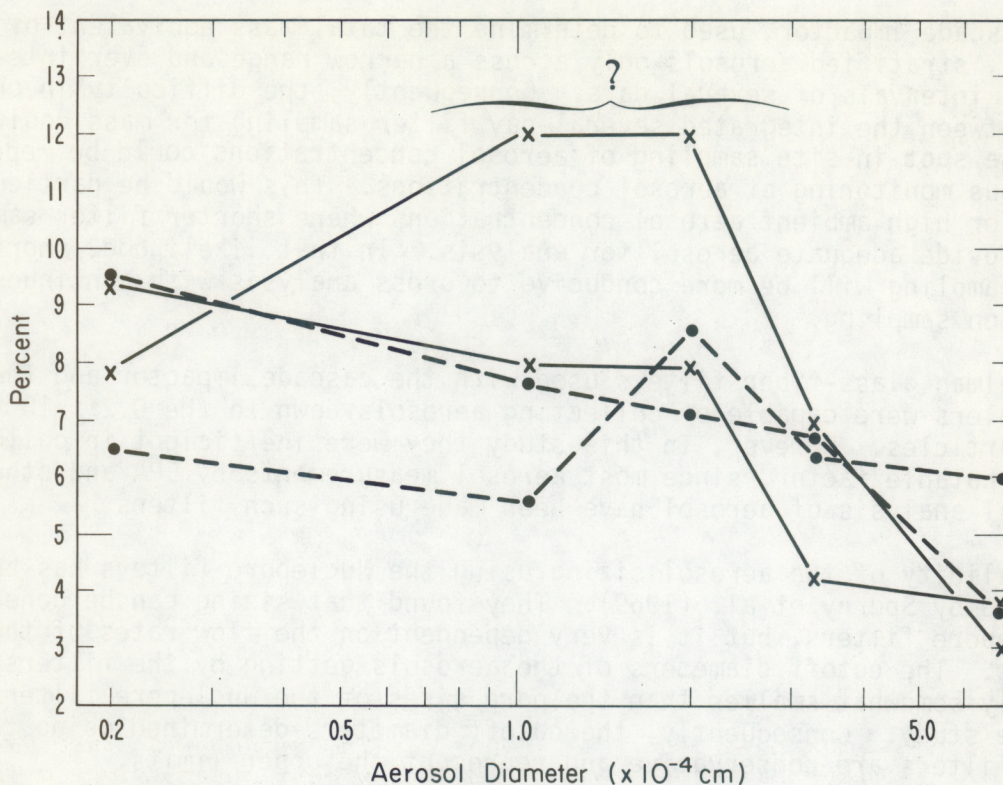
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Figure 9. The organic portion of the aerosol as determined from benzene extractions in relation to the aerosol size. The fractions for the 1.1 x 10⁻⁴ cm to 3.3 x 10⁻⁴ cm sizes are questionable because of the limited amount of aerosol available for analysis.

8. LIMITATIONS, ERRORS, AND VALIDITY OF THE MEASUREMENTS

The major limitations and errors of this study are mainly the result of the height of sampling, the sparcity of observations, and instrumentation.

Critical to the concentrations, mass equivalent, and size spectra of the aerosol sampled was the 1.2-meter elevation exposure of the instrumentation. At this elevation, the larger wind-swept surface particulates loaded the sampling and resulted in mass mean diameters generally above 2.5×10^{-4} cm. Consequently a realistic sampling of aerosol that experiences convective transport to the higher atmosphere over long distances may not have been achieved. More sampling at different heights should be done to investigate what portion of the total surface generated aerosol contributes to the aerosol burden of the troposphere.

Of the instruments used, the Gardner Counter was inadequate in assessing concentrations below 200 CN/cm^3. This was due to limitations characteristic of the Gardner Associates' small particle detector instrument. Relatively few of the observations fell below this level, however, as seen from figures 2 and 3, and so this aspect was not crucial in this study.

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The cascade impactor, used to determine the total mass equivalent of the aerosol, stratified aerosols only across a narrow range and over integrated time intervals of several days. Consequently, the difficulty in cross analysis between the integrated several-day filter sampling for mass equivalent and the spot in-situ sampling of aerosol concentrations could be reduced by continuous monitoring of aerosol concentrations. This would be particularly true for high ambient aerosol concentrations where shorter filter sampling can provide adequate aerosol for analysis. In that likelihood, short term mass sampling will be more conducive to cross analysis with continuous concentration sampling.

The Gelman glass-fiber filters used with the cascade impactor and the Hi-Vol samplers were capable of collecting aerosols down to the 0.2×10^{-4} cm diameter particles. However, in this study they were inefficient in collecting CCN, a notable factor, since most aerosol measurements by EPA and others for chemical analysis of aerosol have been made using such filters.

The validity of the aerosol sizing using the Nuclepore filters has been investigated by Spurny et al. (1969). They found that sizing can be done using Nuclepore filters, but it is very dependent on the flow rates of the sampled air. The cutoff diameters of the aerosols getting by the filters are probably somewhat smaller than the pore sizes of the Nuclepore filters used in the study. Consequently, the cutoff diameters determined using the Nuclepore filters are conservative and represent the upper limits.

A qualitative check of the sizing of the aerosols by the filters can be made by computing for the critical aerosol diameter of CCN (d) for the supersaturations used in the measurements. Using the expression for an insoluble particle, the critical particle diameter will be

$$d = \frac{4 \sigma V_m}{RT (\ln S)} \; ,$$

where d = critical diameter for activation,

σ = surface tension of H_2O,

V_m = molar volume of H_2O,

S = supersaturation with respect to water,

T = temperature, and

R = gas constant.

Letting S = 1.1 and 1.01 and σ = 72 ergs cm^{-2} and V_m = 18 cm^3/mole, critical activation diameters (d) of 0.21×10^{-4} and 0.022×10^{-4} are obtained for supersaturations of 1.01 and 1.1 respectively. The diameters are within the activation sizes of the lower aerosol diameters in figure 4 considering that the hygroscopicity will reduce the activation diameters even more. The observed sizes of the CCN particles also agree fairly well with the results of Whitby and Husar (1971) at the second International Workshop on Condensation and Ice Nuclei. There it was found that for soluble nuclei (NaCl) at supersaturations of 1.3, particles with 0.09 to 0.10×10^{-4} cm diameters were activated.

The size stratifications of the aerosol by the cascade impactor are based on the aerodynamic properties of a sphere having a density of 1 and do not actually describe the size or shape of the aerosol. However, when the hygroscopicity results of the aerosol analysis are reviewed in this light, the effect that a greater surface area and irregular shape could have by adsorbance of water vapor is nil. If a density of 2.5 g/cm^3 is used for the aerosol, the ratio of the surface area to mass of the aerosol collected is

$$\frac{1.2}{r} \frac{cm^2}{gm} \, ,$$

and if it is assumed that a mono-layer of water is adsorbed where one H_2O molecule covers $\leq 10^{-15}$ cm^2, then $1.2 \times 10^{-15}/r$ molecules of H_2O are needed for one mono-layer cover of one gram of aerosol collected, or $3.6 \times 10^{-8}/r \cdot$ gm H_2O/gm aerosol for one mono-layer of H_2O. From Table 3 the mass of H_2O pickup per gram aerosol is $\simeq 3.0 \times 10^{-1}$ gm H_2O/ gm aerosol or three orders of magnitude greater. Therefore in this case the hygroscopicity test rules out the adsorption effect even to five mono-layers thick, and over a ten-fold increase of the surface area. The moisture pickup must be by absorption processes. However, the technique does not describe what the effects of an irregular surface and an increase in surface area have on the absorption process.

Uncertainty in analysis was also introduced in the determination of the organic portion and hygroscopicity of the aerosol. This was particularly true in the analysis of stages two through four of the impactor samples. On these stages, 24- to 48-hour samplings provided a minimum sample for analysis. The ranges of the analyzed results and the maximum percent error for the above stages were determined, where the percent error was:

$$\% \text{ error} = \frac{\text{mass sample - mass blank}}{\text{mass sample}} - 1.00 \tag{8}$$

The organic extractions for stages two through four of the impactor ranged from 3.2 mg to 14.0 mg with maximum errors of 33% to 9%. The ranges for the water absorbence were 16.0 to 89.0 mg and maximum error of 28% to 5%. In all cases, the error could be reduced significantly by extending the sampling time to insure an adequate sample such as the amounts collected on the first stage and the backup filters. In those cases, the error was always within ± 10%.

Finally, the time limitations imposed on the study resulted in a sparcity of data and, therefore, some of the results should not be extrapolated to general conclusions until more data are obtained. This is true for the interpretation of the data with the passage of a frontal system since measurements during only one frontal passage were possible in this study.

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9. CONCLUSIONS

The benchmark properties of atmospheric aerosol must be assessed not from one single measurement but rather from several measurements employing different techniques. Observations in the immediate surface layer at two continental sites, of aerosol concentrations, mass equivalents, and the organic and moisture absorbing portions were made. The results of the measurements were:

(1) Measurements of condensation nuclei to determine the aerosol loading in the near-surface air layer due to wind action and human activity at two continental sites showed net concentrations of atmospheric aerosols ranging from 1.5×10^3 to $1.5 \times 10^5 cm^{-3}$. Ninety percent of these aerosols had diameters greater than 10^{-4} cm. The higher terminal velocities of the $> 10^{-4}$ cm diameter aerosols will prevent long distance dispersion of these aerosols under normal atmospheric conditions.

On the other hand, 60% of the CCN measured had diameters less than 0.2×10^{-4} cm. Consequently the submicron aerosols, which are the most likely to undergo convective transport to higher elevations and subsequent dispersion over greater distances because of their lower terminal velocities, were also the most active as CCN. Although the submicron aerosols comprised only 10% of the total aerosol population measured, they have the highest potential by virtue of transport for contributing to regional atmospheric aerosol burdens as well as the highest potential for participating in cloud physics processes in the atmosphere.

(2) Aside fron concentration levels, no significant differences were measured in aerosol properties from a downtown site and a more remote site $\simeq 5$ km away at the base of the foothills. The downtown site had average concentrations four times those of the remote site.

(3) The hygroscopic aerosols were definitely in the submicron range as is evidenced by the greater moisture pickup by the submicron portion. This difference in the hygroscopity of the submicron aerosols can help to explain the high incidence of activation of the submicron aerosols as CCN at low supersaturations.

(4) The organic portion showed no preference to any particular size. Just as much was found in the submicron aerosols as in those larger than 7×10^{-4} cm. If there is any tendency for the organic portion to aid or hinder moisture pickup and nucleation it was not indicated in the measurement.

(5) Changes in aerosol properties at both sites were observed with a frontal passage. Generally, a lesser hygroscopic aerosol, lower mass median diameters, and a decrease in the organic component were observed after the frontal passage.

(6) While not to the same degree, all aerosol size ranges measured showed properties of hygroscopicity, of an organic component, and of non-nucleating material. Collision and coagulation processes in an initial mixed aerosol population could provide for the eventual presence of all the measured

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properties in all the size ranges examined. Electron microscopy and energy dispersive X-ray analysis of individual aerosols in the Denver area have shown such aerosol composites (Pueschel et al., 1974). In this study, the larger size aerosols measured were largely non-nucleating at low supersaturations and not hygroscopic and, therefore, were probably composed primarily of clays and silicates of surface origin. The submicron aerosols nucleated well at low supersaturations and were hygroscopic and probably were of combustion origin.

The findings of this study reinforce other investigations of atmospheric aerosol. But more important, the study provides a way of investigating several parameters of the aerosol, which is required for proper analysis of the benchmark properties. More observations at different sites and elevations are needed to prove the system. And finally, other measurements, techniques, and systems should be incorporated to update and refine any long-range benchmark measurements of atmospheric aerosols.

10. RECOMMENDATIONS FOR CLEAN-AIR SITES

It was not possible in this study to investigate the scattering and absorbing of incident light by the aerosol. As mentioned earlier, this is an important aspect that must be investigated for a comprehensive analysis of atmospheric aerosol. A recent study at Mauna Loa Observatory describes a method for such investigation at a clean-air site. Resolution of backscatter measurement from aerosols down to 10% of Rayleigh were obtained using an integrating nephelometer (Bodhaine and Mendonça, 1974). Reasonable estimates of continuous total aerosol mass measurements can then be made from the aerosol backscattering by comparing it with Hi-Vol filter sampling.

Condensation nucleus concentration observations made using a Pollak CN counter and a recently developed long tube Gardner CN counter at the same clean-air site in ambient conditions of $\simeq 150$ CN/cm^3 have proved satsifactory. Resolutions down to 10 CN/cm^3 and 40 CN/cm^3 can be obtained from the Pollak and long-tube Gardner counters respectively.

The Gelman Hi-Vol sampler proved inadequate for short-sample aerosol mass equivalent observations at the Ocean-air site. Aerosol mass equivalents as low as 0.3 to 0.9 µg/m^3 in clean-air sampling were observed. Sampling times of more than 175 hours were required to collect a 20-mg sample for analysis. The Gelman Hi-Vol methods proved adequate at a sea-level clean-air site at Kumukahi, Hawaii, where sampling times of 80 hours were sufficient for collecting samples of $\simeq$100 mg of aerosol mass.

Consequently, organic and hygroscopic analysis of the total mass equivalents of aerosols using the techniques of this study, could be used at remote clean-air sites, but may reach the limits of analysis if sampling times are too short. Organic and hygroscopic analysis of mass equivalents across a size spectrum using the cascade impactor at a remote clean-air site is not possible unless extremely long sampling times ($\sim$ 3 weeks) are employed.

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Either a Pollack CN counter or a long-tube Gardner CN counter are adequate for CN concentration observations at a remote clean-air site. Automation of either counter could provide good quality in-situ measurements of aerosol concentrations.

Cloud condensation nucleus measurements have not been attempted on a routine basis by the author at a remote clean-air site as yet, so no evaluation for this type of measurement at clean-air sites can be made at this time.

11. ACKNOWLEDGMENTS

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APPENDIX

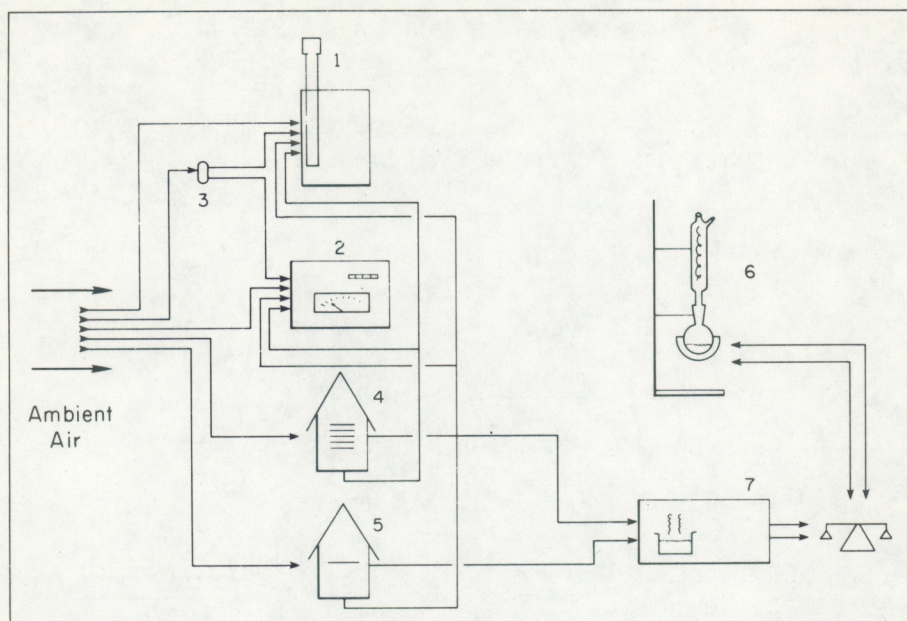## SUMMARY OF AEROSOL INSTRUMENTS AND MEASUREMENTS

Figure A.1. Instruments in schematic flow of measurements.

1 - Aitken Particle Counter (Number Concentration)
   $0.001\mu < r < 5.0\mu$—s.s. $\approx$ 200.0

2 - Cloud Condensation Counter (Number Concentration)
   $0.01 < r < 5.0\mu$—s.s. 1.01 and 1.10

3 - Nuclepore Filters (Size Distribution) Cutoff Windows Measured.
   $0.001\mu < r < 8.0\mu$; $0.003\mu < r < 1.0\mu$;
   $0.005\mu < r < 0.5\mu$; $0.009\mu < r < 0.2\mu$

4 - High-Volume Impactor (Aerosol Mass vs. Size)
   50% Cutoff Diameters—7.0μ; 3.3μ; 2.0μ; 1.1μ and 0.2μ

5 - High-Volume Filter Sampler (Total Aerosol Mass)
   Glass-Fiber Filter—Cutoff Diameter $\approx 0.2\mu$

6 - Soxhlet Extraction (Organic Portion of Aerosol)
   Benzene—Solvent Strength, $\epsilon = 0.32$
   Samples measured from High-Volume Impactor stages and from
   High-Volume Filter Sampler.

7 - Gravimetric Measurements of Aerosol Hygroscopicity.
   Exposure Humidities—30%, 74%, 80%, 93%. Samples measured from
   High-Volume Impactor stages and from High-Volume Filter Sampler.

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ENVIRONMENTAL RESEARCH LABORATORIES

The mission of the Environmental Reasearch Laboratories is to study the oceans, inland waters, the lower and upper atmosphere, the space environment, and the earth, in search of the understanding needed to provide more useful services in improving man's prospects for survival as influenced by the physical environment. Laboratories contributing to these studies are:

Atlantic Oceanographic and Meteorological Laboratories (AOML): Geology and geophysics of ocean basins and borders, oceanic processes, sea-air interactions and remote sensing of ocean processes and characteristics (Miami, Florida).

Pacific Marine Environmental Laboratory (PMEL): Environmental processes with emphasis on monitoring and predicting the effects of man's activities on estuarine, coastal, and near-shore marine processes (Seattle, Washington).

Great Lakes Environmental Research Laboratory (GLERL): Physical, chemical, and biological, limnology, lake-air interactions, lake hydrology, lake level forecasting, and lake ice studies (Ann Arbor, Michigan).

Atmospheric Physics and Chemistry Laboratory (APCL): Processes of cloud and preciptation physics; chemical composition and nucleating substances in the lower atmosphere; and laboratory and field experiments toward developing feasible methods of weather modification.

Air Resources Laboratories (ARL): Diffusion, transport, and dissipation of atmospheric contaminants; development of methods for prediction and control of atmospheric pollution; geophysical monitoring for climatic change (Silver Spring, Maryland).

Geophysical Fluid Dynamics Laboratory (GFDL): Dynamics and physics of geophysical fluid systems; development of a theoretical basis, through mathematical modeling and computer simulation, for the behavior and properties of the atmosphere and the oceans (Princeton, New Jersey).

National Severe Storms Laboratory (NSSL): Tornadoes, squall lines, thunderstorms, and other severe local convective phenomena directed toward improved methods of prediction and detection (Norman, Oklahoma).

Space Environment Laboratory (SEL): Solar-terrestrial physics, service and technique development in the areas of environmental monitoring and forecasting.

Aeronomy Laboratory (AL): Theoretical, laboratory, rocket, and satellite studies of the physical and chemical processes controlling the ionosphere and exosphere of the earth and other planets, and of the dynamics of their interactions with high-altitude meteorology.

Wave Propagation Laboratory (WPL): Development of new methods for remote sensing of the geophysical environment with special emphasis on optical, microwave and acoustic sensing systems.

Marine EcoSystem Analysis Program Office (MESA): Plans and directs interdisciplinary analyses of the physical, chemical, geological, and biological characteristics of selected coastal regions to assess the potential effects of ocean dumping, municipal and industrial waste discharges, oil pollution, or other activity which may have environmental impact.

Weather Modification Program Office (WMPO): Plans and directs ERL weather modification research activities in precipitation enhancement and severe storms mitigation and operates ERL's research aircraft.

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