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AN ASSESSMENT OF WARM FOG - NUCLEATION, CONTROL, AND RECOMMENDED RESEARCH

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16. ABSTRACT

This report presents a state-of-the-art survey of warm fog research which has been performed up to, and including, 1974. Topics covered are nucleation, growth, coalescence, fog structure and visibility, effects of surface films, drop size spectrum, optical properties, instrumentation, liquid water content, condensation nuclei. Included is a summary of all reported fog modification experiments. Additional data is provided on air flow, turbulence, a summary of recommendations on instruments to be developed for determining turbulence, air flow, etc., as well as recommendations of various fog research tasks which should be performed for a better understanding of fog microphysics.

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FOREWORD

This report is a state-of-the-art survey of warm fog research which has been performed up to, and including, 1974. Its purpose was to identify basic research problems which must be solved before techniques can be developed to effectively modify and dissipate warm fogs. During the survey, considerable literature was reviewed to identify those research tasks being done by other government agencies, as well as university and industry research teams. This approach allows NASA to identify those research tasks which are not being studied, to develop a more coordinated research plan, and eliminate unnecessary duplication of research.

Based on the results of this survey, a list of needed research tasks were identified, and they have been classified as to their importance.

The work reported herein was conducted under the Technical direction of Mr. Otha H. Vaughan, Jr., of the Aerospace Environment Division, Space Sciences Laboratory, Marshall Space Flight Center. Mr. John Enders, Chief of the Aviation Safety Technology Branch, NASA, Office of Aeronautics and Space Technology, provided encouragement and the necessary support for the accomplishment of this survey.

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Chapter 1

INTRODUCTION

This report is designed to meet the following objectives. The effort involves a literature search and analysis only; no laboratory or field investigation is included. The stated objectives, as designated in RFQ 8-1-3-75-30063-RSF, 9 July 1973, deal with two tasks:

Task I Assess the influence of specific pollutants (which we define as natural, anthropogenic or artificial foreign materials producing an advertent or inadvertent effect) on warm fog behavior and seedability. Identify those condensation nuclei which are most effective in producing and stabilizing warm fog. Compare the available experimental results, on both the laboratory and field scale, of nucleation efficiency with the theoretically predicted values.

Task II Assess the state of the art in warm fog research and provide a report listing by priority the basic research tasks that are required to help resolve the unknowns in warm fog modification and control achieved through processes involving nucleation and growth processes initiated by additions of foreign materials. This assessment should point out the expected opportunity for obtaining realistic solution to the problems.

The problems which we will address will include (a) increase in visibility at airport runways and their approaches, (b) increase in visibility along heavily travelled highways, (c) fog stabilization to decrease frost hazard in agriculture (d) assessment of the magnitude of inadvertent fog production and stabilization by anthropogenic contaminants. It should be noted that the stress of this report is toward the behavior of foreign materials (sometimes loosely termed nuclei) on the formation, stabilization and dissipation of warm fogs. Little attention is paid to other standard procedures for fog modification involving artificial increase in temperature, air motion and the like. It is obvious that turbulence and turbulence-induced processes play significant roles in fog and fog modification including that by foreign materials. In fact, the heterogeneous microphysics and turbulent mixing are strongly interrelated and the apparent separation of these two considerations in this report arises primarily from convenience.

Chapter 2

FOG PROPERTIES AND THE MICROPHYSICS OF FOG FORMATION

2.1 Introduction

A fog is defined as a cloud whose base touches the ground. Hence
the properties of a fog are those of a cloud and the formation mode of
a fog is identical to that of a cloud in terms of its microphysics.
Thus the basic information obtained in the consideration of cloud
properties and formation modes may be applied, with some restrictions,
to fogs.

2.1.1 Nucleation

The phase transition leading to fog formation, namely the water
vapor to liquid transition, occurs in the atmosphere exclusively by the
heterogeneous nucleation route. The nuclei may function in two ways:
(1) through a solution process decreasing the equilibrium water vapor
pressure over a solution droplet and (2) through an adsorption process
on the surface of a solid insoluble particle. In general the solution
mechanism involving hygroscopic materials occurs at relative humidities
less than 100 percent; the adsorption mode always requires supersatura-
tion.

We will deal here exclusively with nucleation on hygroscopic
substrates. Note that the substrate may be either a liquid, such as
sulfuric acid, or a solid, such as sodium chloride or the various sul-
fates found in polluted atmospheres. The equilibrium vapor pressure
over a solution may be approximated as a function of concentration and
temperature by Raoult's Law or may be directly measured. The growth
rate of the solution droplet may be then computed, at least in the
first approximation. Some equilibrium values are calculated in Table 2-1
for a hygroscopic solid, NaCl, assuming Raoult's Law is valid.

TABLE 2-1

Equilibrium Relation Between NaCl Particle Size and Solution Droplet Radius

Relative Humidity	$r_{droplet}/l_{particle}$
0.98	2.5
0.99	3.2
0.995	4.0
0.997	4.7
0.998	5.4
0.999	6.8
0.9995	8.6

These equilibrium values are of significance only with respect to
a limit. The actual droplet size is a function of water vapor concen-
tration gradient, growth time and residence time of the growing
particle in the region of high relative humidity.

The nuclei concentration and size produce major effects in fog (cloud) properties. A maritime cloud is formed with relatively low concentrations of nuclei but large-sized hygroscopic nuclei. The result in the competition for water vapor is the production of a relatively low concentration of fairly large droplets. In the continental situation the nuclei concentration is large, the nuclei particles are small and the resulting cloud contains high concentrations of the smaller droplet sizes. Significant cloud properties thus include (a) liquid water content, (b) droplet size distribution (in a dynamic sense) and (c) nuclei concentration (with some measure of hygroscopic capability and size distribution). We will consider later the problem of instrumentation to obtain these measurements conveniently, precisely and under dynamic situations.

Obviously fog properties may be altered by the addition of a nucleant to an existing fog. The liquid water and water vapor will redistribute tending toward an equilibrium configuration dependent upon nucleant properties and initial particle size. Fog dissipation upon the addition of a nucleant may occur through (a) a change in fog droplet size distribution which serves to increase coalescence rates, initiate precipitation and thus decrease liquid water content, (b) a change in droplet size distribution and concentration which leads to the formation of fewer, larger droplets and hence an increase in light transmission (visibility), (c) a charging of the water droplets which may increase coalescence and (d) a surface tension effect which may lead to increased coalescence efficiency. The stabilization of fogs upon the addition of a foreign material may lead to (a) an enhanced colloidal stability in that the liquid water must distribute to form many smaller droplets, (b) a reduction in both evaporation and condensation rates and (c) an electrical double layer effect which may reduce coalescence efficiency.

2.1.2 Droplet Growth

In principle any cloud or fog is thermodynamically unstable; the system must tend toward the production of very large drops with minimum surface area. It is possible, however, to consider a fog as a quasi-equilibrium configuration in which we apply equilibrium concepts to the concentration of a droplet solution as a function of water vapor concentration (see Table 2-1). Even this treatment, however, although it provides an upper limit for droplet size, is unsatisfactory in its application to cloud processes. A kinetic treatment must be employed in which the rate of droplet growth must be measured or computed as a function of initial nucleant particle size, nature of nucleant, water vapor pressure as a function of location and time, and residence time of the growing droplet. Included implicitly in the terms listed above are diffusion rates under a concentration gradient, effects of temperature and its accompanying thermophoretic effects.

The rate of droplet growth is also affected by any surface change which will alter the rates of evaporation or condensation; i.e., transport through a surface film into the bulk of the droplet. The presence of such a film is always marked by a highly significant descrease in surface tension. Obviously those conditions surrounding

decrease in surface tension. Obviously those conditions surrounding a cloud or fog droplet which determine its growth rate are a function of atmospheric motion involving both steady flow and turbulence.

2.1.3 Coalescence

The coalescence via collision of two fog droplets is given in terms of a collision number (number of collisions per unit time) and a coalescence efficiency (fraction of successful collisions). It is not too difficult, in terms of current theory, to calculate the collision number as a function of droplet size, temperature and droplet concentration; some question exists, however, regarding the effects of turbulence. The second term, coalescence efficiency, is not well understood and may possibly be a function of electrical charge, surface structure, collision angle, etc.

One possible mode of fog dissipation is the mechanism by which droplets grow to sufficient size to permit high coalescence rates with the eventual formation of precipitation-size drops which fall to the ground.

2.1.4 Fog Structure and Visibility

Since the radius of a fog droplet is on the order of 10 microns, or approximately 10 times the wavelength of visible light, the scattering occurring in fogs is described by the Mie theory. The amount of light absorption by liquid water is negligible and hence the visibility is determined by scattering only. For an assemblage of fog droplets the loss in light intensity by Mie scattering is directly proportional to the droplet concentration and to the square of the droplet radius. At constant liquid water content in a fog, the concentration of droplets is given by K/r^3 in which r is the droplet radius. The loss in light by scattering is thus measured by $Kr^2/r^3 = K/r$ in the first approximation and hence as r increases the scattering decreases and visibility is improved. Any process which can decrease droplet concentration, such as the formation of precipitation, will improve visibility. In a tradeoff situation in which no liquid water is lost, the effect of particle concentration with respect to particle size dominates.

We propose in the detailed discussion below to consider these microphysical processes in detail with respect to their significance in the dissipation, stabilization and formation of warm fogs. We will, on the basis of a literature survey, analyze the current state of the art both in theory and practice. This analysis will then lead to a statement of unsolved problems, of required theoretical development, and of necessary instrumentation. Possible solutions will be considered only in terms of laboratory scale investigations.

2.2 Nucleation

In any phase transition process an energy barrier exists such that generally the transition does not occur at a measurable rate under equilibrium conditions. The theory of this energy barrier and corresponding transition rates has been developed for (a) homogeneous

nucleation, (b) nucleation by an insoluble liquid-wet solid substrate, (c) nucleation by an insoluble non-liquid-wet substrate and (d) nucleation on a liquid soluble substrate. These theories are in essentially suitable form for use in fog studies (Mason, 1957, Fletcher, 1966).

We may immediately disregard two of the above mechanisms. Neither homogeneous nucleation nor nucleation on the surface of an insoluble, non-liquid wettable substrate occurs at supersaturation rations existing in the atmosphere. It is highly improbable that any hydrophobic surface can be converted to a hydrophilic surface by an atmospheric process.

2.2.1 Nucleation on an Insoluble, Water-wet Substrate

If a solid exhibits zero contact angle with respect to a liquid it is termed "wet"; if the liquid is water it is termed "water-wet". From theory dealing with homogeneous nucleation, a critical size embryo is defined as one that will spontaneously grow; it is the minimum size that can lead to the formation of a liquid phase. This critical embryo is thus a nucleus and its size is a function of super-saturation ratio, temperature, water surface tension and water molar volume as expressed in the Kelvin equation. Some typical critical embryo radii are given in Table 2-2 for water at 10C.

TABLE 2-2

Critical Embryo Radii for the Homogeneous Nucleation of Water

S(Supersaturation Ratio)	r^*(microns)
1.002	0.569
1.005	0.228
1.008	0.142
1.010	0.114

For embryo of this size the energy barrier is such that condensation does not occur, i.e., the probability of embryo formation is essentially zero. Consider, however, the process of physical adsorption on the surface of a water-wet insoluble solid. Under these circumstances the film formed at water saturation is a "duplex" film; i.e., the upper surface possesses the surface characteristics of liquid water. Such a particle coated with a duplex film is thus identical to a water embryo of the same size (the film thickness is negligible with respect to particle radius). Thus such a particle would serve as a condensation nucleus if its radius equalled or exceeded the critical radii given in Table 2-2. In terms of nucleation processes a knowledge of the concentrations of such particles is important.

Such water-wet insoluble solids may be "poisoned" if their surface characteristics are so altered as to produce a non-zero contact angle with water. Such poisoning may be quite common; any person who has dealt with glass surfaces knows it forms water droplets, while on a clean glass surface water sheets and exhibits zero contact angle. A water-wet surface is basically a high energy surface; it will tend to pick up any substances which will reduce its surface energy and as a

consequence display an increased contact angle toward water (Shafrin and Zisman, 1949). It is thus necessary to consider not only the role played by water-wet insoluble solids as condensation nuclei but the effect of anthropogenic substances, primarily of the organic type, as poisons.

A general principle states that at an interface a substance will be adsorbed (concentrated) if it provides a gradual transition from the polar environment of the condensed phase to the much less polar environment of the gas phase. Thus an amphipathic substance (a molecule containing a polar and non-polar portion) orients itself at an interface on which it is strongly adsorbed to present the non-polar (hydrophobic) portion to the gas phase. The adsorption of such a molecule on an initially hydrophilic surface thus converts it into a strongly hydrophobic surface. The long chain alcohols, acids, and acid salts fall into this category. It has been further observed (Archer and La Mer, 1955; Eisner et al.,1960; Derjaguin et al.,1966) that a close packed monolayer of long chain alcohols and acids will cause a drastic reduction in both evaporation and condensation rates of the water subphase existing below the monolayer. Such substances can thus act in a dual mode; (a) by affecting the efficiency of cloud condensation nuclei by converting the surfaces and (b) by affecting the growth rate of water on the embryos so formed or on existing cloud droplets. In this section we consider only mode (a). It is possible that such nuclei poisoning could occur in the downwind pollution plume from a large source.

Experiments designed to evaluate such possible nucleant poisoning have been carried out by Bigg et al.(1969). These workers treated an incipient fog with cetyl alcohol on "the assumption that the alcohols will tend to condense only on the condensation nuclei if fog has not already formed," and asked the question "Will indiscriminate coating of all the condensation nuclei with alcohol lead to the desired effect?" Note that such condensation nuclei are both soluble and insoluble so that these experiments will not answer questions regarding effects of surface coating on insoluble hydrophilic materials. These authors conclude, "The results that we have obtained are consistent with our having prevented fog throughout a large volume of air but provide no certain evidence that this would not have happened naturally." They compare the desirable field experimentation to such studies in weather modification which require a very large number of experiments with and without random seeding in order to obtain statistical verification of the seeding effect.

Laboratory experiments in the Cornell Aeronautical Laboratory 600 m^3 cloud chamber have been reported by Kocmond et al. (1972). Again in these studies no attempt was made to differentiate between soluble and insoluble cloud condensation nucleants. These workers added both cetyl and oleyl alcohols to existing fogs, dissipated the fogs thermally and reexamined the visibility and droplet size spectrum of fogs produced on the coated nuclei thus present with respect to the properties of control fogs. They find (a) with cetyl alcohol it was quite possible

that the initial fog was not completely dissipated but marked differences were observed between the droplet size spectrum in the treated and control; the droplet sizes in the treated fog were consider-able smaller. Since the cetyl alcohol may act both as a nucleant poison and by altering evaporation and condensation rates interpretation is difficult; (b) with oleyl alcohol the fog was completely dissipated. The second fog produced on the treated condensation nuclei was essen-tially identical in visibility to the control; (c) treatment of the initial fog with cetyl alcohol for times up to 50 minutes in the dis-sipation mode caused almost complete dissipation (see (a); time for dissipation of the untreated fog was approximately 20 minutes). When the fog was reformed little difference was observed between the cetyl alcohol treated system and the control in both visibility and drop size spectrum; (d) when condensation nuclei were pretreated with cetyl alcohol prior to any fog formation, little difference in visibility with respect to the control was observed. The droplet size spectrum, however, indicated major differences attributed primarily to retard-ation of droplet growth.

The experiments cited do not provide a definite answer to the poisoning question raised above since (a) only a complex mixture of natural condensation nuclei were employed and (b) the experimentation involved growth rates as well as nucleant effects. It might be instructive to determine cloud condensation nuclei concentrations on artifically produced hydrophilic insoluble nucleants both with and without cetyl alcohol pretreatment.

2.2.2 Soluble Cloud Condensation Nuclei

Basically such a nucleant begins to dissolve and form a saturated aqueous solution at a vapor pressure of water equal to that over the saturated solution. It may be easily show that, for a cubic salt particle having a 0.1 micron edge, Kelvin lowering of the vapor pressure over the saturated solution is negligible. The theory of nucleation of a liquid by a hygroscopic soluble nucleant is adequately treated by Fletcher (1966) and Mason (1957). By consideration of the critical embryo radius for homogeneous nucleation as shown previously it is obvious that a 0.1 micron salt particle readily provides an embryo of saturated solution which will grow.

Soluble cloud condensation nuclei are employed in fog dissipation experiments on the theory that the fog droplets corresponding to an equilibrium water vapor concentration over a salt solution close to saturation are larger than the droplets occurring in natural fogs. The liquid water content is then distributed into fewer but larger droplets and visibility is improved. This theory will be considered later. The basic problem lies in a dynamic study of the pickup of water vapor by such growing solution droplets as they traverse the fog. The time scale for the formation of the initial saturated solution droplet may be estimated in the following fashion. From kinetic theory the rate of collision of gas molecules with a unit area surface may be readily calculated. For NaCl at 10C, the collision rate is

given as a function of cube edge as $v = 2 \times 10^{22} L^2$ collisions per second. It is assumed the pressure of water vapor is that over a saturated NaCl solution. One may also compute the number of water molecules in such a saturated solution as a function of initial NaCl cube edge as $n_{HOH} = 2.1 \times 10^{23} L^3$. For an accomodation coefficient of unity the time required to form such a solution is 10L; for an accomodation coefficient of 0.1 (a reasonable lower limit) the time required is 100L. Thus with an initial cube edge of 0.1 micron the maximum formation time of the saturated solution is estimated 0.001 seconds and that for a 10 micron cube edge 0.1 seconds. Nucleation time is thus not a major factor in laboratory or field scale experiments.

The effect of possible pollutant concentration on the nucleating capability of hygroscopic nuclei can be considered as the sum of several interactions. That which we consider in this section is inhibition of the nucleation process; in later sections we consider the effects on growth of the water embryo and resulting solution droplet.

In general it is difficult experimentally to evaluate the possible effects of pollutants on the nucleation characteristics of soluble nucleants; this is due to the fact that such pollutants affect growth rates as well as nucleation and it is difficult in laboratory or field investigations to separate the two effects. In other words (a) does the pollutant so decrease the water uptake by the nucleant that the critical embryo is not obtained or (b) does it so affect the growth of such an embryo that water (solution) droplets are not observed to affect visibility?

We define nucleation as that process leading to the formation of the critical embryo; we will consider the growth of such a critical embryo to a solution droplet in Section 2.3. The question then arises: does the presence on the surface of a soluble nucleant of a foreign substance inhibit critical embryo formation in respect to equilibrium or rate? If the soluble particle is sufficiently large so that the Kelvin effects may be ignored, the presence of an insoluble contaminant on the nucleant surface cannot affect its equilibrium with water. Any effects thus must be rate effects.

It has been demonstrated by La Mer and a number of other workers (La Mer, 1962) that the presence on the surface of liquid water of close-packed films of straight long chain acids and alcohols markedly decrease the rate of evaporation of water through the film. This subject has been thoroughly discussed by Davies and Rideal (1961). It has been further conjectured that these films will likewise affect condensation rates (i.e., markedly decrease the sticking coefficients). Only close packed films produce this effect; in such films the area occupied per molecule is on the order of 20 A^2 and the concentration on the order of 5×10^{14} molecules per cm^2. In theory one would predict that the rates of condensation would also be affected if the subphase is a solid rather than liquid water and one might therefore expect an effect on the rate of water pickup by a soluble nucleant and hence the rate of formation of the critical embryo. If the rate is sufficiently reduced a poisoning effect results.

Jiusto (1964) reported the effect of treating NaCl crystals with hexadecanol and octadecanol by various methods; (a) the NaCl crystals were dissolved in a liquid suspension of the monolayer-forming material and in pure water. The salt crystals were recovered by drying. It was noted that the drying times were substantially prolonged in the presence of the long chain alcohol. This merely attests to a lowered evaporation rate from the solution. The dry crystals were then subjected to water vapor at relative humidities of 90 to 100 percent; no measurable difference in water uptake rate was observed. It has been previously demonstrated that the long chain compound must be rigidly oriented on a surface to produce any measurable effect; it is doubtful whether the coating obtained by evaporation of an aqueous solution is so oriented. One might expect blobs rather than an oriented monolayer; (b) the NaCl was dusted with solid long-chain compound; no effect was observed with NaCl dusted with kaolinite; retardation rates up to a factor of three were observed with NaCl dusted with octadecanol and hexadecanol.

Pilié (1966) reported that NaCl crystals coated with hexadecanol by treatment with a petroleum ether solution of the long chain compound were prevented from dissolving at relative humidities up to 90 percent. Concentrations of hexadecanol in the petroleum ether were adjusted to obtain uniform coatings. With such a coating treated crystals are observed to pick up water much more slowly than controls. This author concludes that treated nuclei are not deactivated but the effect is one of growth retardation. The measurement techniques, in our opinion, simply cannot distinguish between the two processes.

A feasibility calculation seems in order. It has been reported by Derjaguin et al. (1966) that the equilibrium vapor pressure over hexadecanol at 20C corresponds to a concentration of 1.4×10^{-10} grams/cm^3. By application of ideal gas behavior we calculate a vapor pressure of 1.4×10^{-8} atm. These authors indicate that a monolayer is formed on liquid water at a relative pressure of 0.1; we assume that a monolayer is formed on a soluble mucleant particle at the same relative pressure. The equilibrium vapor pressure at monolayer equilibrium is thus 1.4×10^{-9} atm and the vapor phase concentration 1.4×10^{-11} gram/cm^3 or 1.4×10^{-5} grams/meter^3. Assume a concentration of 500 such nucleant particles per cm^3, a cube edge of 0.1 microns and a roughness factor of 10. The number of grams of hexadecanol required to form a monolayer on this nucleant is 6×10^{-7} grams/m^3. The amount remaining in the vapor phase is thus negligible with respect to the amount adsorbed. If one attempts to treat a 4×10^6 cubic meter air mass one would thus require a minimum of 2.4 grams of the alcohol. The process is thus feasible.

This analysis, however, contains a highly improbable assumption; namely, that the adsorption of hexadecanol is not affected by the presence of other adsorbable species. We would expect competition with water vapor to form a mixed absorbed layer. It has been show by La Mer and others that the evaporation retardation is marked only if the hexadecanol film is at least 99 percent complete. Coadsorption, therefore, would eliminate poisoning based upon condensation rates.

It is obvious that further experimental observations are required to fully understand the poisoning of soluble nucleants by either

synthetic additives such as long chain alcohols or inadvertent additives such as may exist in a pollution plume.

A question may arise concerning the poisoning of soluble nucleants by substances present in polluted air other than surface active materials. Thus, for example, one might convert a soluble species to an insoluble species by chemical reaction. This would be quite unlikely to occur with the alkali metal salts since all these compounds are essentially highly water soluble. The alkaline earths, however, including calcium and magnesium might possibly be converted to such insoluble species as calcium or magnesium oxalate. No attention to this possible factor has been evidenced in the literature.

2.2.3 Polyelectrolytes as Nucleants

Several attempts have been made to use polyelectrolytes to disperse warm fogs. The concept leading to these attempts concerned the pickup of such materials by small water droplets, the creation of a high charge density on these droplets and finally coalescence resulting from this charge distribution.

In general, these materials have not proved effective in warm fog dispersal. It has been suggested that their residence time within the fog is too short to permit a major takeup of water.

Some polyelectrolytes, such as the polyacrylamides, which may be obtained in a molecular weight range of 0.5 to 10 million, possess the ability to swell enormously in liquid water. It is not uncommon to find swollen spheres of 99.99 percent water content and apparent sizes in the micron range. Given the opportunity to so swell a particle of initial radius of one micron could swell to a size of 20 microns, while a three micron particle could swell to 60 microns. These effects are observed in liquid water; the presence of salt causes a somewhat reduced water pickup but presumably could increase the rate of water pickup from the vapor. It is suggested attempts be made to treat the polyelectrolyte with salt prior to its introduction into the cloud and employ the swelling rather than electrical characteristics as the rationale for use in warm fog dispersal.

2.3 Growth of Fog Droplets

The degree to which a fog attenuates transmitted electromagnetic radiation depends on the concentration and drop size spectrum of the droplets and the wavelength of the radiation. As the fog droplets grow they may become sufficiently large to fall out in the gravitational field; this precipitation removal process is a function of the drop-size spectrum and change of spectrum with time. Large drops also are more effective as collectors of smaller droplets than the small drops; the efficiency of the coalescence growth process is thus a function of drop-size spectrum. The change in drop-size spectrum with time and the associated changes in transmissivity of light and fog dissipation via precipitation may be most conveniently treated from the standpoint of dynamics. Hence, in the following treatment, we do not discuss

equilibria in constrained systems or the thermodynamics of steady state situations.

The change in droplet size spectrum may be accomplished through removal of liquid water by evaporation, through droplet growth by condensation, by nucleation (discussed previously) and by coalescence and precipitation.

The droplet size spectrum may be defined by a number of relations:

1. A continuous plot of number concentration versus droplet radius in both a differential and cumulative sense.

2. A discrete plot (bar graph or histogram) of number concentration versus droplet radius.

3. Similar plots for droplet mass as a function of radius.

4. Similar plots for the fraction of total droplets versus radius.

From these distributions one may calculate the distribution statistics; e.g., number median radius, mass median radius, etc., as well as standard deviations and the like. The experimental means of determining droplet size distributions and a critique involving such measurements will be considered later in a section on instrumentation.

2.3.1 Growth by Condensation

Condensation is defined as the net transition of a substance from the vapor to the liquid phase. Growth by condensation occurs only after an embryo has reached (passed) critical size; it is thus differentiated from nucleation. In a molecular sense condensation occurs when the rate at which vapor molecules strike and merge with a liquid surface is greater than that of vaporization. Condensation and vaporization are dynamic processes and occur simultaneously. The rate of growth is thus a sum of three processes: (1) the number of vapor molecules per unit time which strike the droplet surface, (2) the fraction of such molecules which stick, and (3) the rate at which molecules leave the liquid surface for the vapor.

For any kinetic process one may consider an energy barrier which effectively determines the rate of this process. For the transfer to or from a water droplet three such energy barriers exist: (1) transfer of molecules between the bulk liquid and the interface, (2) transfer across the interface, and (3) transfer between the interface and bulk vapor. Barrier (1) is significant only if poor mixing occurs within the droplet; in a growing fog droplet sufficient condensation heat is released to provide such stirring that the process applicable to this barrier no longer becomes rate determining. For a clean surface (in the absence of foreign materials) barrier (2) is effectively constant and is reflected in the "condensation coefficient"; the behavior of close packed foreign surface films involves primarily their effect on this barrier. In general, the rate determining step for particle growth is vapor phase diffusion; some effect is attributed in small drops to a rate contribution from the interface transfer process.

The treatment of both Fletcher and Mason regarding drop growth considers a vapor phase concentration gradient set up by vapor phase depletion in the immediate vicinity of the growing droplet and the diffusion rate of water vapor to the droplet as a function of this gradient. In addition account must be taken of the heat transfer from the droplet as influenced by heat of condensation. Some refinement has been introduced into this simple theory by Fukuta and Walter who have compared their results with a less complex model. Mordy has discussed the possible change in condensation coefficient with drop size.

The Fletcher theory for a nonventilated drop has been used in models for fog dissipation by Jiusto et al., 1968; Chu and Thayer, 1972; and Weinstein and Silverman, 1973. The growth treated is that of a droplet containing a water soluble salt. This theory seems adequate for such modeling purposes in the lack of sufficient experimental information to warrant development of a more complex theory or to provide sufficient data for the calculation of ventilation factors.

The Fletcher theory takes the form

$$r(dr/dt) = G(S-(a/r) + (b/r^3))$$

in which G is a complex function involving a diffusion coefficient, densities of the liquid and vapor, latent heat of condensation, molecular weight of water, temperature and thermal conductivity. The term S is the supersaturation ratio minus unity. Since the term a/r refers to Kelvin effects it becomes negligible for drop sizes greater than about one micron (an effect less than 0.1 percent). For larger drops containing no solute dr/dt is thus GS/r. For constant supersaturation the rate of growth is thus inversely proportional to r and the system tends toward monodispersity on growth. For a soluble species and a droplet radius greater than 1.0 micron the growth expression becomes $dr/dt = GS/r + Gb/r^4$. Since the term b/r^4 drops off very rapidly with particle growth and since its magnitude is dependent upon the initial mass of the soluble species its effects cannot readily be generalized. In the limit, however, when both the terms in a/r and b/r^3 are negligible the growth rate is essentially GS/r.

Some consideration must be paid to the term S in the above relation. Since the equilibrium vapor pressure over liquid water is a function of temperature, S will be a function of the pressure of water vapor and the temperature. The formation of a fog is due to a decrease in temperature or the addition of water vapor at constant temperature. The temperature decrease may occur in many ways, e.g., adiabatic lifting, advection, radiation, etc. Since, however, S in a dynamic system containing growing fog droplets must change with time as water vapor is removed, its time derivative is a function of droplet growth. This effect must be considered in any fog growth models. The direct experimental measurement of S as a function of time is currently not feasible. One of the difficulties in such a measurement is the effect of the measuring instrument on the value of S in the vicinity of the instrument. Attention also should be paid to the variation in S in the vicinity of the growing particle by the release of latent heat as

the particle grows. Thus as a fog is incipient S increases; upon nucleation and droplet growth S decreases and as long as growth continues must remain at a value slightly greater than zero.

2.3.2 Evaporation of Fog Droplets

In a nucleant-seeding process small droplets must disappear to provide a water source for the growth of the larger seeded droplets. With this redistribution in droplet size spectrum the visibility will be improved. Thus, the evaporation rate from the small droplets is important in modelling.

Evaporation involves the same processes as condensation; namely a dynamic process involving the collision and adherence of vapor phase molecules to the liquid and departure of water molecules from the liquid to the vapor. In evaporation the departure rate is greater than the gross collection rate.

The same three energy barriers apply. For slight subsaturations the rate determining step, except for very small droplets, is the vapor phase diffusion and the theories developed for condensation apply here as well. The rates of both evaporation and condensation will be markedly affected by ventilation, especially for the larger droplets. The rate of evaporation is a function of the subsaturation. The net loss of water by this process is thus a function of both degree of subsaturation and the time interval at which such subsaturation exists. Jiusto et al. (1968) have used Fletcher's equation (given earlier) to calculate the time required for a droplet of given size containing the equivalent of a 0.1 micron NaCl crystal to evaporate to the equilibrium size at a set of subsaturations. Closer examination of Figure 1 in this publication, however, casts some doubts about the validity of the calculation made for a subsaturation of 99.99 percent (see Fig. A-1). These times substantiate the theory that hygroscopic particles are effective within a real cloud in altering the droplet size spectrum.

The assemblage of fog droplets comprising a fog contains both small and large droplets consisting of pure water or very dilute solution. These droplets will undergo evaporation at suitable subsaturations. The assemblage will also contain small droplets of very concentrated solution which will grow. The mass water flux from a small pure water droplet is less than that from a large pure water droplet since $-dm/dt = kr$ in the absence of Kelvin effects and $kr - k'$ in the presence of Kelvin effects. The mass transfer to the vapor is then a function of droplet size distribution with greater weight on the larger pure water droplets.

Very few experiments have been performed on the evaporation rates of droplets in the size range usually found in fogs and under fog environmental conditions. Most experiments studied the evaporation of droplets over a wide range of sizes and at low relative humidities. Among these experiments are those of Houghton (1933), who measured evaporation of droplets supported on glass filaments or fine wires with radii from

12.5 to 1300 microns at various relative humidities and Derjaguin et al. (1966), who measured the evaporation of droplets, suspended on a glass filament, initially 300 microns in radius in an environment of 40 percent relative humidity. Their results, smoothed over the entire range, support the theory based on vapor diffusion as the rate-determining step. Hoffer and Mallen (1970), measuring the evaporation rate of droplets supported by an upward-moving air stream, also found good agreement with this theory for droplets between 20 and 70 microns when they included a ventilation factor given by Frössling. They do not give any values of the relative humidity. Duguid and Stampfer (1971), measuring the evaporation of 3-9 micron drops at a high relative humidity (96-99 percent) also found that this theory best predicted the observed results. The observed evaporation rates were slightly higher than those calculated, which may be due to ventilation effects. It would appear, then, that the vapor phase diffusion theory, one form of which is given by Fletcher, is adequate for consideration of the evaporation of fog droplets.

2.3.3 The Effect of Surface Films

Close packed monolayers of long straight-chain alcohols, acids and acid salts act to considerably increase the barrier to transport across the water-vapor interface. This effect can be considered as a reduction of the condensation coefficient from about 0.04 (for pertinent reference seek Fukuta and Walter, 1970) to $2-4 \times 10^{-5}$ (Derjaguin et al. (1966), Eisner et al. (1960). The surface film is effective in reducing transport only if transport through the interface is the rate determining step; if the rate determining step is vapor phase diffusion no effect on gross transport rates is observed (Archer and La Mer, 1955). Nevertheless marked effects of cetyl alcohol monolayers on evaporation have been demonstrated in unstirred vapor systems by Derjaguin et al., and in a very large number of experiments on the effect of cetyl alcohol on evaporation rates from lakes and ponds in still air.

Evaporation rates of water droplets may be observed microscopically into still or stirred air maintained at various relative humidities. The film may be added in close packed form or achieve the close packed configuration by a reduction in surface area caused by evaporation.

Derjaguin et al. (1971) studied the growth of small solution droplets of varying solute concentration covered with a close packed monolayer of cetyl alcohol and placed in a continuous flow of air saturated with both cetyl alcohol and water vapor. They found that adsorption of the alcohol was sufficient to maintain an effective coating on the droplet surface as long as the water supersaturation did not exceed seven percent. The experimental details presented were too vague to permit an estimate of validity.

Other experiments performed on droplet populations were discussed in Section 2.2.1. As noted there, it is impossible to distinguish in these experiments between the effects of a surface film on nucleation and effects on growth.

The effects of close packed surface films on the condensation and evaporation of water droplets near water saturation are not well known

and should be further investigated. It seems unlikely that surface active materials in anthropogenic products can form close packed monolayers; their effect, if any, must be on the nucleation process.

2.3.4 Coalescence

Coalescence in a warm fog can lead to a shift in droplet size spectrum to larger sizes. The coalescence of fog droplets is a result of two processes: (1) droplet collision and (2) droplet merging.

The calculation of collision number for freely falling drops is essentially a problem in hydrodynamics; one can no longer use a simple kinetic expression relating to the droplet velocities, concentration and collision cross section but the flow around the large drop serves to decrease the collision number deduced from kinetic theory. The term "collision efficiency" has been defined in the literature in terms of two drops of radii a_1 and a_2 and the radius of a cylinder in which the small drop must exist in order for a collision to occur. Thus $E = y^2/(a_1 + a_2)^2$ in which y is the cylinder radius. Some rather crude approximations were made by Hocking (1959) and later refined by Hocking and Jonas (1970). This problem especially relating to the coalescence of fog droplets has been discussed by Shafrir and Neiburger (1963) and Klett and Davis (1973). Collision efficiencies so plotted are presented by these authors.

In his original paper Hocking reported no collisions occurred if the collector drop radius was eighteen microns or less; in the later paper of Hocking and Jonas no definite cutoff was considered but rather the fact that collision efficiencies for small collector drops were low. It is interesting to compare the collision efficiencies as calculated by these authors; these are presented in Table 2.3.

TABLE 2-3

Collision Efficiencies as Calculated by Several Authors

a_1/a_2

a_1	0.2			0.4			0.6			0.8		
	HJ	SN	KD	HJ	SN	KD	HJ	SN	KD	HJ	SN	KD
10	.005		.02	.01		.04	.02		.05	.02		.05
20	.007	0	.03	.03	0.1	.11	.06	0.3	.2	.04	0	.14
30	.03	.2	.14	.4	0.9	.5	.7	1.3	.6	.5	1.2	.5
40		.5	.4		1.2	.7		1.6	.8		1.7	.8

It should be noted that considerable disagreement exists.

The actual number of collisions per unit volume is a function of the collision efficiency, the particle concentration and the particle size distribution. No way has as yet been found to measure directly the collision efficiency since experiments always yield the number of droplets of increased size, which is a function both of collision and

coalescence efficiency. The latter is defined in terms of the fraction
of successful collisions; i.e., those leading to droplet merger. Coales-
cence efficiency has been studied by a number of workers. Use of a
droplet stream directed at a suspended drop is reported by List and
Whelpdale (1969) and Whelpdale and List (1971) and a droplet stream
directed at a plane or convex surface is considered by Schotland (1960),
Jayaratne and Mason (1964) and Pilié (1966). In all these studies the
drop sizes are larger than those encountered in warm fogs. All studies
dealing with droplet sizes in the warm fog range involved the product
of collision and coalescence efficiencies; these experiments will be
discussed later.

No quantitative theory of coalescence efficiency for small droplets
has been developed, but a number of workers have postulated the existence
of barriers to coalescence. As reviewed by Whelpdale and List (1971)
these include (1) an air film between the drops which must be expelled,
(2) the energy requirements to distort the droplet surface (which
involves the dynamic rather than static surface tension) and (3) elec-
trical double layer repulsion. Attraction is provided by the "enhanced
van der Waals forces" discussed by Davies and Rideal (1961).

Factors which have been observed to affect coalescence include
velocity of collision, impact angle, surface tension (dynamic or static?)
and the presence of an electrical charge on the particle or an electric
field. Most of these factors have been studied for collisions with a
large suspended drop or a flat surface. The effects of velocity and
impact angle relate to the energy and time available to remove the air
film barrier and to distort the drop surface. Lower velocities at high
incident angles (near the edge of the collector drop) often resulted
in bouncing or partial coalescence rather than complete coalescence.
List and Whelpdale (1969) found that a lower surface tension increased
coalescence while Pilié (1966) found the opposite effect. It is
questionable that static surface tension values are significant especially
in the presence of surfactants; the dynamic values in this latter case
may be considerably higher and not markedly affected by the surfactant.
At fog droplet sizes and collision velocities surface tension effects
may be of significance. What should be investigated are the surface
terms in the dynamic sense, i.e., both tension and viscosity. The
presence of surface active materials (both advertent and inadvertent)
may affect these surface parameters.

Studies of collection efficiencies of droplets in the fog droplet
range (r less than 40 microns) give contradictory results. Telford
et al. (1955) found very high collection efficiencies (on the order of
13) for 75 micron collector drops. Measurements have been reported by
Kinzer and Cobb (1958) and Telford and Thorndike (1961) which support
the Hocking theory and Woods and Mason (1964) which support the Shafrir
and Neiburger calculations if the coalescence efficiency is unity.
Levin et al. (1973) measured collection efficiencies, compared their
results with the calculated values of Shafrir and Neiburger and
attributed the differences noted at a_2/a_1 greater than 0.1 to departure
of the coalescence efficiency from unity. Whelpdale and List (1971)
found somewhat similar results with larger drops.

The effects of turbulence have been neglected or suppressed in all studies noted. In order to have any effect on growth by coalescence, the scale of turbulence must be small enough so that the relative motion of the droplets is affected. Since there is some evidence that turbulence may increase coalescence rates, this factor should be examined. It is further discussed in Chapter 3.

Strong electrical fields have been found by all workers to greatly enhance coalescence (Telford, et al. 1955; Whelpdale and List, 1971; List and Whelpdale, 1969 and Telford and Thorndike, 1961). The difficulty of producing such fields over the area to be cleared in fog dissipation activities inhibits the practical use of this phenomenon. Due to the low collision efficiencies of droplets in the fog size range and the uncertainties in coalescence efficiency, it is difficult to determine the effectiveness of the coalescence effect in fog modification. Further study should be made of the collection efficiency as a function of droplet size ratio and of possible methods to increase coalescence efficiency. The effect of small scale turbulence should also be investigated (see Chapter 3 for a discussion of different turbulent processes which enhance coalescence).

2.3.5 Drop Size Spectrum

As noted earlier, the supersaturation ratio within a warm fog changes with time due to two opposing processes: (1) decrease in water vapor saturation pressure by cooling, or water vapor pickup from a source outside the fog and (2) decrease in water vapor content due to droplet nucleation and growth. When the first process predominates the supersaturation increases. Since different nuclei (size and composition) are activated at different supersaturation ratios, more drops will be formed with increasing supersaturation and the existing drops will grow faster as well. The second process then becomes predominant and the supersaturation begins to decrease.

The number of nuclei activated at a given supersaturation depends on the time interval experienced by the particle at that or a higher supersaturation. This effect has been noted with ice nuclei (Gerber, 1973) with the observation that the nucleation rate is a function of supersaturation and particle size. Similar rate effects should exist for condensation nuclei although the subject has not been thoroughly studied. In any event, the nucleant must reside at the proper supersaturation for a time sufficient to form an embryo of critical size.

The result of this supersaturation "history" is that a wide spectrum of droplet sizes may exist when the supersaturation decreases to a steady state value as the droplets have existed for varying lengths of time and have grown at different rates. For example, droplets grown on hygroscopic nuclei begin growing at subsaturation and grow more rapidly than droplets on insoluble hydrophilic nuclei. For solution droplets formed on hygroscopic nuclei the growth rate depends upon not only cloud saturation conditions but also the nature and size of the nucleant particle. For water droplets formed on insoluble hydrophilic nuclei formation depends on saturation conditions and nucleant particle

size. Some potential nuclei are not activated; either the peak
supersaturation is too low or the time of residence in the supersaturation
regime is too short. Thus we are led to an initial wide dispersion in
the drop size spectrum.

As the fog ages the spread of the distribution decreases. This is
due to the relatively faster growth rate of the small droplets. The
drop size distribution within a fog is thus a function not only of the
original size spectrum but also of the age of the fog. Since only a
very small number of droplets in natural fog are large enough to have
reasonably high collision efficiencies as observed by Pilié and Kocmond
(1967), the coalescence process seems unlikely to have much effect on
altering the droplet size distribution with the possible exception of
the bottom of a thick fog layer.

2.3.6 Seeding with "Giant" Hygroscopic Nuclei

When large (greater than 0.5 micron) hygroscopic particles are
placed in a slightly supersaturated environment, nucleation occurs
almost immediately and droplets are formed. As the nucleant concentration
in the droplet is high initially, the first stages of growth are very fast
and water vapor is rapidly removed from the environment. This causes a
decrease in water vapor concentration and hence degree of saturation.
If subsaturation is reached, the natural fog droplets may begin to evapo-
rate. So long as the growth rate on the new nuclei is sufficiently
great to take up the water vapor thus made available, the subsaturation
is maintained. Given sufficiently large and numerous nucleant particles,
a few large droplets will exist while the natural droplets, especially
the small ones, will disappear through evaporation. This change from a
droplet size distribution of many small droplets to one with a few
large droplets will improve visibility. In addition, if these droplets
formed on the giant nuclei are sufficiently large they will settle out
gravitationally, may in this fallout coalesce with some of the remaining
smaller droplets, and reduce the liquid water content of the fog. This
leads to a still greater increase in visibility.

This mechanism provides the rationale for use of giant hygroscopic
nuclei in warm fog dissipation. Both laboratory and field investigations
have been directed toward the use of this method. These will be dis-
cussed more fully in the matrix section of this report. The complexity
and detail of the experiments vary widely; references will be provided
in the matrix section.

As noted earlier, the time required for droplet evaporation is
related to the degree of subsaturation. This latter in turn is affected
by removal of the droplets formed on giant nuclei by settling and hence
the residence time within the fog of such droplets. In addition more
water vapor may be introduced into the seeded portion of the fog by
molecular and turbulent diffusion. Computer models of such addition
(Chu and Thayer, 1972, Weinstein and Silverman, 1973) have indicated
considerable detriment on the effectiveness of seeding with giant
hygroscopic particles.

2.4 Optical Properties of Fogs

2.4.1 Introduction

The prime objective of warm fog dissipation is the increase in visibility (related to the visual portion of the electromagnetic spectrum). Probably the prime objective in fog stabilization, other than for military reasons, is minimization of freezing damage in crop growth; this is related to the transmission through the fog of radiation in the infrared region of the spectrum.

The interaction of an assemblage of fog droplets with radiation may occur through (1) absorption and (2) scattering. The absorption of light in the visible wavelength range by water in vapor or droplet form is essentially negligible and may be dismissed from further consideration; this may not be true in the infrared in which both liquid water and water vapor have strong absorption bands. The absorption effect is determined primarily by the concentration of water substance and hence any increase in concentration (increase in liquid water content at saturation) will affect IR absorption.

Scattering may be treated in terms of Rayleigh theory or Mie theory. The former is applicable only when the size of the scattering particle is small compared with the radiation wavelength. For Rayleigh scattering in the visible this size is on the order of 0.03 microns; in the infrared it may be a factor of four greater. The droplet size spectrum in a fog is thus well beyond the applicability of the Rayleigh theory.

2.4.2 Mie Scattering from Fog Droplets

This discussion will be limited. We will not enter into the basic theory, the fundamental physics of the process or the application to such possible studies as droplet size distribution, etc. Rather we will present the basic equations dealing with the effect on gross attenuation in the forward direction (transmissivity) as a function of particle size distribution. In the literature review we encountered little agreement with respect to notation. Since much of the work on warm fog dissipation has been done at the Cornell Aeronautical Laboratory we will employ here the notation of Jiusto et al. (1968). The Mie scattering Coefficient, β, is defined for a single spherical particle as

$$\beta = \pi r^2 k_s$$

in which k_s is termed the scattering area coefficient. As a matter of notation β is termed σ by Penndorf (1956), and k_s by Johnson (1954) while k_s in the Jiusto notation is termed K by Penndorf (total Mie scattering coefficient) and K_s by Johnson (scattering cross section). For an assemblage of particles

$$\beta = \Sigma \pi N_i r_i^2 k_{si}$$

Thus if β and k_s are known one has a measure of $\Sigma N_i r_i^2$.

The scattering area coefficient, k_s, is a complex oscillating function of the ratio of particle size to radiation wavelength. For visible light and typical fog droplet sizes, k_s approaches the value two; this value has been taken by Jiusto et al. (1968) which gives

$$\beta = 2\pi \Sigma N_i r_i^2$$

The visibility, V, is given by 3.912/β.

Consider a sample calculation. Let the initial fog have a liquid water content of 0.15 gram/m^3 with all the liquid water in 10 micron droplets. The droplet concentration is thus 3.6×10^7/m^3. One then calculates β 2.25×10^{-4}cm^{-1} and V - 174 meters. Let us now alter the distribution to one containing one-fourth of the original 10 micron droplets with the remaining liquid water in 30 micron droplets. The number of these would be 9.9×10^5. One then calculates β as 1.125×10^{-4}cm^{-1} and V = 348 meters. If the larger droplets fall out of the fog, the visibility again doubles. Obviously this is a crude example. Since $\beta_i = 2\pi N_i r_i^2$ (in which $k_{si} = 2$) and since the liquid water content, $w_i = N_i 4\pi r_i^3/3$, we can write $\beta_i = 3w_i/2r_i$. From the cloud droplet size distribution in terms of number versus droplet size, we can obtain a mass, or w_i, distribution by multiplying by $4\pi r_i^3/3$. This can be converted into a β_i distribution against size. The total Mie scattering coefficient is then obtained as a sum over this distribution and the contribution of the various sizes to the total scattering becomes clearly apparent. We have made such calculations for the data of Kornfeld (1970) and present the calculations in Table 2-4 and Figure 2-1. The effect of seeding is an increase in scattering by the small and large droplets, and a considerable decrease in scattering from the middle range of droplet sizes, resulting in a net decrease of scattering by the fog.

2.5 Instrumentation

2.5.1 General Comment

We have emphasized the dynamic character of fogs and the fact that dynamic characteristics are predominant in attempts to modify such fogs. It is therefore necessary that the instrumentation employed to determine fog characteristics and the response of fogs to modification efforts have the dynamic characteristics required.

2.5.2 Supersaturation Ratio

This is a basic fog characteristic and in principle determines the efficiency of any added artificial nucleant, bears upon the initial cloud droplet size spectrum and hence number concentration and influences the growth and evaporation processes. It is essentially a measure of relative humidity. Dew point devices and psychrometers are used routinely at relative humidities less than 100 percent; severe questions

TABLE 2-4

The Size Distribution of the Mie Scattering Coefficient

r_i	N_i	$w_i \times 10^{12}$	$\beta_i \times 10^8$
		Initial Fog	
1	2	8	.13
2	18	603	452
3	75	8482	4241
4	120	32169	12063
5	75	39270	11781
6	18	16286	4071
7	2	2873	616

$$\beta = 3.32 \times 10^{-4} cm^{-1}$$

		Fog 100 Seconds After Seeding	
.33	2	.3	1.3
.66	18	22	50
1.0	75	313	470
1.3	120	1199	1346
1.8	75	1960	1597
2.6	18	1325	764
7.5	2	3561	710
17.8	1	23532	1986
26.2	1	75627	4324
31.4	1	129446	6187

$$\beta = 1.74 \times 10^{-4} cm^{-1}$$
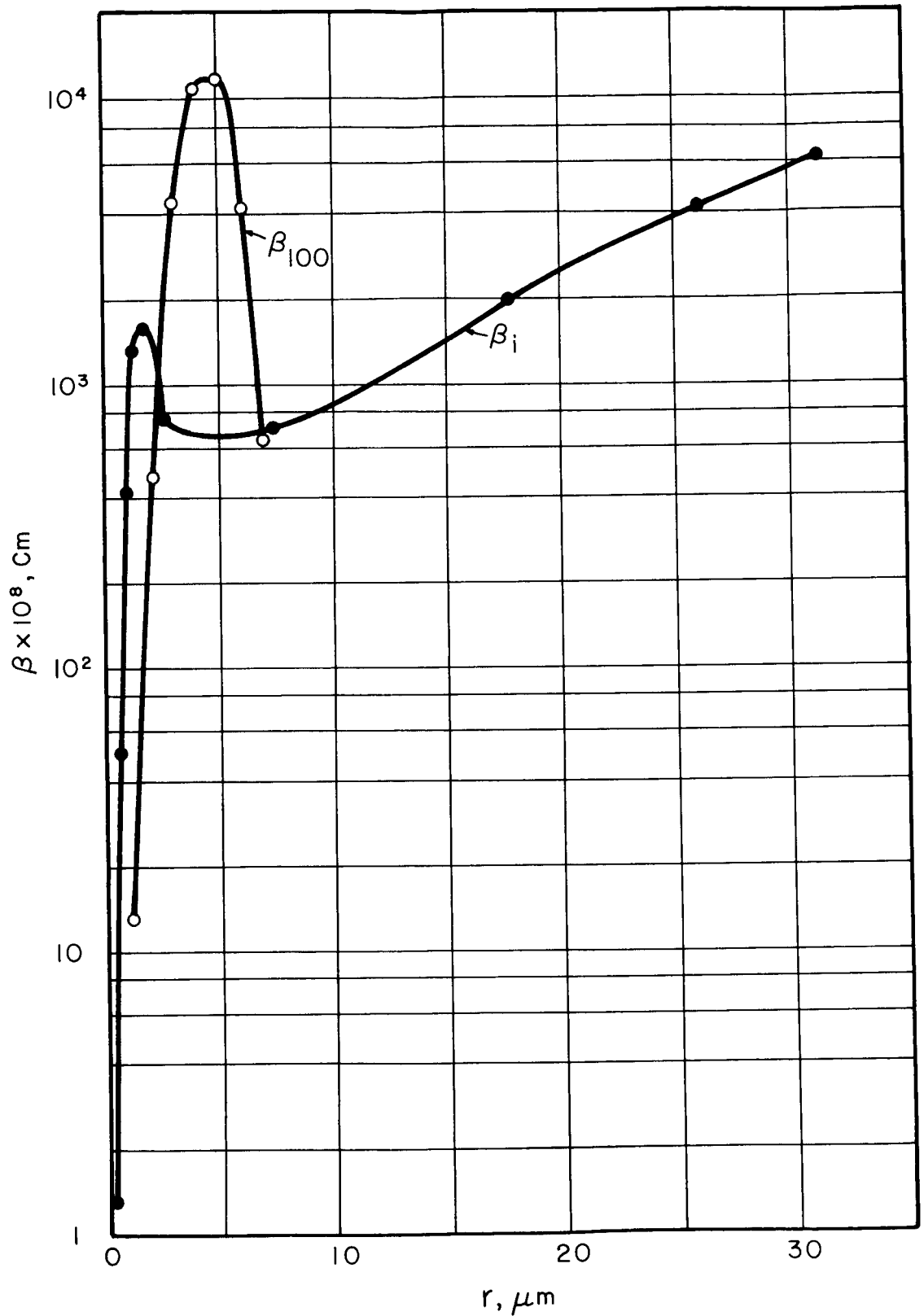
Fig. 2-1 The size distribution of the Mie scattering coefficient:
curve β_i is for initial fog and curve β_{100} is for fog
100 seconds after seeding.

exist concerning their capability at supersaturation ratios slightly less than or greater than unity.

Laboratory Instrumentation. The degree of supersaturation may be computed for laboratory experiments utilizing expansion techniques by assuming (1) adiabatic (or corrected) expansion, (2) lack of condensation nuclei activated during the expansion and (3) no wall losses. Supersaturation gradients may be computed for thermal or chemical gradient diffusion devices. Supersaturation ratios may also be computed from a knowledge of drop size spectrum and the particle size and nature of added nucleants. Supersaturation may also be produced from a water reservoir at fixed temperature greater than the measuring chamber, etc.

Field Instrumentation. The supersaturation ratios are largely inferred from the cloud droplet concentration and size spectrum and knowledge of the nature, concentration and size of nucleants. To a large extent this value is simply assumed.

Conclusion. A clear need exists for the development of an instrument useful in both the laboratory and the field for the determination of supersaturation ratios. This instrument must have a suitable dynamic response, should be portable and usable by technicians. No ideas are forthcoming by the authors for the working principles of such an instrument.

2.5.3 Properties of Condensation Nuclei

These properties may be classified as (1) chemical nature (vapor pressure of water above solution as a function of concentration), (2) size and (3) number concentration.

Chemical Nature. No problem exists in this regard for artificial nucleants. For natural nucleants several techniques exist or offer possibilities. If a sufficient quantity can be collected standard methods of chemical analysis including X-ray fluorescence, atomic absorption, X-ray diffraction, etc., may be used to determine the composition of the gross sample. For particles greater in size than 0.05 microns the composition of the particle surface may be determined by electron fluorescence techniques used in conjunction with a scanning electron microscope and hence individual particle compositions determined; this method will not work for first row elements in the periodic table (carbon, nitrogen, oxygen, etc.). A technique has been developed by Mendonca and Corrin which measures the water uptake by a total sample as a function of relative humidity; this is, of course, a total method. It may readily be converted to an automatic instrument. Measurements obtained with Fort Collins, Colorado aerosol have indicated the initiation of water vapor pickup at relative humidities ranging from 65 to 74 percent relative humidity. If the aerosol is fractionated by use of Nuclepore filters, the initial point of water pickup varies with particle size. It might be interesting to extract the collected aerosol and measure the surface tension of its solution; this would indicate the presence of surface active material which might tend to alter nucleation characteristics. If one wished to proceed further with this

analysis, foam fractionation would yield additional information on the chemical nature of the surface active material.

Size. Collected material may be analyzed for particle size distribution by electron microscopy providing the material is stable in the electron beam. An estimate of particle distribution may be obtained for particles greater than 0.3 microns with a cascade impactor. Smaller sizes may be measured with a Goetz aerosol spectrometer. The use of expansion condensation nuclei counters to provide particle size infor- mation by counting as a function of supersaturation cannot be considered satisfactory since the number activated is a function of parameters other than size. Possibilities exist for particle size determination via light scattering but this technique is fraught with major complica- tions. Mention should be made of the fact that size may be determined geometrically as with a microscope or aerodynamically as with the Goetz or cascade impaction.

Number Concentration. The basic technique involves exposing potential condensation nuclei to an environment supersaturated with respect to water vapor and observing the number of droplets formed. Since the number of nuclei activated is a function of supersaturation ratio, this value must be controlled and be similar to those observed or expected in actual atmospheric situations. It is generally limited to 0.95 to 1.03.

The device most often used is the thermal diffusion chamber (see the discussion, for example, in Ruskin and Kocmond, 1971). Chemical gradient chambers have also been utilized (see the discussion in Fletcher, 1966). As pointed out by Ruskin and Kocmond (1971) other attempts to produce controlled low supersaturations have not been successful.

Differences among thermal diffusion chambers include (a) chamber geometry, (b) continuous or discontinuous operation and (c) techniques for counting the number of water droplets. In most chambers the sample is introduced between horizontal plates. In a listing of then existing chambers by Saxena and Kassner (1970), nine of the eleven chambers discussed were of this horizontal type. Other chambers involve vertical concentric cylinders (Severynse, 1964; Laktionov, 1968) or vertical parallel plates (Sinnarwalla and Alofs, 1973). Most chambers operate in the discontinuous mode; nine of the chambers discussed by Saxena and Kassner were of this type.

Methods of detecting droplet number include direct photography (Pilié, 1966; Gagin and Terliuc, 1968; Saxena et al. 1970; Allee, 1971; and Ruskin and Dinger, 1971), integration of scattered light (Radke and Hobbs, 1968 and Radke and Turner, 1972), and direct counting of droplets by individual scintillations excited by a beam (laser or otherwise) (Laktionov, 1968; Hudson and Squired, 1973 and Sinnarwalla and Alofs, 1973). A "haze chamber" suitable for use at subsaturations is described by Kocmond and Jiusto (1968).

Some use has been made of so-called Aitken counters in the low supersaturation regime; these instruments cannot be considered suitable for this purpose.

Conclusion. Available instrumentation for the determination of cloud nucleus concentrations is adequate. Caution, however, should be directed toward the possible use of this technique for particle sizing.

2.5.4 Liquid Water Content

A commonly used instrument is the hot wire liquid water content meter as discussed by Knollenberg (1972) with reference to Neel and Steinmetz (1952), Neel (1955) and Owens (1957). This technique is limited to drops less than 30 microns (Barrett, 1958) and is unsatisfactory at low droplet concentrations.

Another such instrument is the paper tape liquid water content device of Warner and Newnham (1952). This involves the change in con- ductivity of a suitably prepared paper tape upon permeation by collected water. Sensitivity has been reported as low.

The total liquid water content may also be estimated by integration of the droplet size distribution. Knollenberg has discussed such a technique. In the laboratory the liquid water content of a simulated cloud may be estimated by heating a portion of the cloud to vaporize all liquid water, determining the dew point and assuming a supersaturation ratio of unity.

Conclusion. Given the high concentration of droplets in a fog and the relatively small number of large drops, present hot wire techniques seem adequate for the measurement of the liquid water content of initial fogs. An appreciable population of large drops, such as might result from modification, cannot be handled with present instrumentation other than the tedious integration over a particle size distribution.

2.5.5 Droplet Size Distribution

Such instrumentation may be classified into (1) collection devices and (2) in situ devices.

Collection Devices. These may consist of slides coated with silicone oil, magnesium oxide, gelatin, formvar, etc. Corrections must be applied to the measured area to convert into droplet size and for collection efficiencies as a function of droplet size. Cylinders may be employed with this technique. Measurements may be made microscopically and a distribution curve thus produced. Commercial devices are also available to compute particle size distributions from the collected particles or a photograph.

In Situ Devices. Direct photography has been utilized by Berg and George (1968), Cannon (1970) and Neiburger et al. (1972). Optical arrays have been employed by Knollenberg (1972), Knollenberg and Neish (1969) and Knollenberg (1970). An electrostatic device has been described by

Abbott et al. (1972). Infrared transmittance forms the basis of a method described by Eldridge (1957) and light scattering techniques have been used by Eldridge (1961) and Ryan et al. (1972). The attenuation of light has been utilized by Eldridge (1966) while holographic techniques have been described by Kunkel (1970 and 1971).

Conclusion. With the possible exception of droplets whose diameters are less than one micron the measurement capability for particle size distributions in fogs seems adequate.

2.5.6 Visibility

Two devices are in use: (1) visual observation and (2) transmissometers. Visibility should be properly defined in terms of the objectives of fog dissipation efforts; i.e., shall it be "vertical visibility," "horizontal visibility" or some suitable combination? Should measurements be made at ground level or in an aircraft or some suitable combination? Should spectral characteristics be considered (the eye is most sensitive to green light)?

2.6 Information Matrix: Fog Modification Experiments

1. REFERENCE   INVESTIGATOR(S)   PUBLICATION DATE
   Preprints Third Conf.   E.E. Hindman II   June 1972
   on Weather Modification
   Rapid City, S.D.   ORGANIZATION   SPONSOR
                                                Naval Weapons Center   Navy

       2. OBJECTIVE   3. PHYSICAL BASIS   4. EXPERIMENT TYPE

       Increase Visibility   Alter Drop Size Distribution and LWC   Field

5. INITIAL PARAMETERS   Median drop diameter, drop number density, liquid water content, precipitation
   rate, fog depth, wind shear, wind turning, visual estimate of visibility (not clearly defined)

6. PROCESS MODE   Spray of "exceedingly" hygroscopic solution (composition not stated).   Volume rate
   of spray noted.

7. FACTORS CONSIDERED IN NUMERICAL MODELS

8. PARAMETERS AFTER TREATMENT   Median diameter, number density, liquid water content, precipitation
   rate, fog depth, wind shear, wind turning

9. CONCLUSIONS   (1) Small wind turning necessary for success.   (2) Low liquid water content
   required for success.   (3) Wind shear is not critical.

10. COMMENTS   A poorly designed and described experiment.   Insufficient data given for evaluation.
    Quality of data questionable.   Only three observations.

1. REFERENCE
Preprints Third Conf.
on Weather Modification
Rapid City, S.D.

INVESTIGATOR(S)
B.A. Silverman, A.I. Weinstein,
B.A. Kunkel and L.D. Nelson

ORGANIZATION
AFCRL

PUBLICATION DATE
June 1972

SPONSOR
AFCRL

2. OBJECTIVE

Improve Visibility

3. PHYSICAL BASIS

Alter Drop Size Distribution

4. EXPERIMENT TYPE

Field

5. INITIAL PARAMETERS   Wind speed and direction, relative humidity, visibility, liquid water content, drop size and fallout rate (not defined), fog depth, temperature

6. PROCESS MODE   Sized, micro-encapsulated urea (known size distribution)(nature of encapsulation not described)

7. FACTORS CONSIDERED IN NUMERICAL MODELS

8. PARAMETERS AFTER TREATMENT   Ground instrumentation (presumably initial parameters), aircraft observer response

9. CONCLUSIONS   (1) Feasible to properly position seeding aircraft.   (2) Microencapsulated urea may be suitable for fog dissipation.   (3) More accurate wind information needed.   (4) Airborne line seeding is not operationally feasible (must use wide-area techniques).

10. COMMENTS   Data does not support conclusions (our opinion); it is insufficient

1. REFERENCE
    Proceedings Int. Conf.
    on Weather Modification
    Canberra, Australia

    INVESTIGATOR(S)
    P. St. Amand, R.S. Clark, T.L. Wright,
    W.G. Finnegan, and E.A. Blomerth, Jr.

    ORGANIZATION
    Naval Weapons Center

    PUBLICATION DATE
    September 1971

    SPONSOR
    Navy

2. OBJECTIVE
    Improve Visibility

3. PHYSICAL BASIS
    Decrease Liquid Water Content

4. EXPERIMENT TYPE
    Field

5. INITIAL PARAMETERS   Fog type, top and area, wind, pressure, temperature, dew point, liquid water
    content, drop size distribution, visibility, ceiling, precipitation type and amount

6. PROCESS MODE   Ammonium nitrate-urea water solution, seeding rate, air delivery

7. FACTORS CONSIDERED IN NUMERICAL MODELS

8. PARAMETERS AFTER TREATMENT
        Ceiling, visibility, temperature increase, relative humidity,
    liquid water content

9. CONCLUSIONS   (1) Ceiling and visibility can be improved by seeding stable fog.   (2) Effect and
    rate of effect are a function of seeding mass

10. COMMENTS   Results based on data from 7 of 19 experiments

1. REFERENCE
NASA Contractor
Report NASA CR-1731

INVESTIGATOR(S)
W.C. Kocmond, R.J. Pilie, W.J. Eadie,
E.J. Mack and R.P. Leonard

PUBLICATION DATE
April 1971

ORGANIZATION
Cornell Aeronautical Laboratory, Inc.

SPONSOR
NASA

2. OBJECTIVE

Improve Visibility

3. PHYSICAL BASIS

Alter Drop Size Distribution

4. EXPERIMENT TYPE

Field

5. INITIAL PARAMETERS   Drop size distribution, drop concentration, liquid water content, visibility, fog depth

6. PROCESS MODE   Aerial seeding with both sized and unsized NaCl, Na_2HPO_4, $CO(NH_2)_2$ and polyelectrolytes

7. FACTORS CONSIDERED IN NUMERICAL MODELS

8. PARAMETERS AFTER TREATMENT   Drop size distribution, drop concentration, liquid water content, visibility

9. CONCLUSIONS   (1) Can improve visibility in dense valley fog.   (2) Most effective in latter stages of fog.   (3) Turbulence, winds greater than 10 knots and high liquid water content make seeding impractical.   (4) Sized material most effective.   (5) Single test shows polyelectrolyte ineffective

10. COMMENTS

1. REFERENCE
NASA Contractor
Report NASA CR-1731

INVESTIGATOR(S)
W.C. Kocmond, R.J. Pilie, W.J. Eadie,
E.J. Mack and R.P. Leonard

ORGANIZATION
Cornell Aeronautical Laboratory, Inc.

PUBLICATION DATE
April 1971

SPONSOR
NASA

2. OBJECTIVE
Improve Visibility

3. PHYSICAL BASIS
Alter Drop Size Spectrum

4. EXPERIMENT TYPE
Field

5. INITIAL PARAMETERS   Visibility, temperature, relative humidity, CCN, drop size distribution, drop concentration, dew point, wind speed and direction

6. PROCESS MODE   Polyelectrolytes (unspecified as to nature and size)

7. FACTORS CONSIDERED IN NUMERICAL MODELS

8. PARAMETERS AFTER TREATMENT   Visibility, drop size distribution, drop concentration, liquid content, temperature, dew point, time

9. CONCLUSIONS   No fog clearing was produced by nucleant addition

10. COMMENTS   Only one test. Nature of nucleant unknown. Hardly a conclusive experiment

1. REFERENCE
Preprints Second Conf.
on Weather Modification
Santa Barbara, California

INVESTIGATOR(S)
B.A. Silverman and T.B. Smith

ORGANIZATION
AFCRL and MRI

PUBLICATION DATE
April 1970

SPONSOR
AFCRL

2. OBJECTIVE

Improve Visibility

3. PHYSICAL BASIS

Drop Size Distribution

4. EXPERIMENT TYPE

Field

5. INITIAL PARAMETERS   Visibility, temperature, liquid water content, turbulence, drop samples (not further described), fog depth and backscatter flux

6. PROCESS MODE   Sized NaCl (size ranges given), seeding mass

7. FACTORS CONSIDERED IN NUMERICAL MODELS

8. PARAMETERS AFTER TREATMENT   Visibility (transmissometer), drop size (not further defined), time, total water removed (not further described)

9. CONCLUSIONS   (1) Visibility improved.   (2) Turbulence plays a major role.   (3) Large amount of NaCl are required to treat a 500 foot thick fog

10. COMMENTS   Poorly described experiments

PUBLICATION DATE
February 1969
SPONSOR
CSIRO

1. REFERENCE
   J. Appl. Met.

   INVESTIGATOR(S)
   E.K. Bigg, J.L. Brownscombe and W.J. Thompson
   ORGANIZATION
   CSIRO

4. EXPERIMENT TYPE
   Field

3. PHYSICAL BASIS
   Deactivate CCN

2. OBJECTIVE
   Prevent Fog Formation

5. INITIAL PARAMETERS   CCN, drop size distribution, drop concentration, air motion (balloon), ice nuclei, temperature

6. PROCESS MODE   Mixture of long-chain alcohols added from smoke generator

7. FACTORS CONSIDERED IN NUMERICAL MODELS

8. PARAMETERS AFTER TREATMENT   CCN concentration, ice nuclei concentration, drop size and concentration of precipitation, fog position

9. CONCLUSIONS   No evidence that effect was due to treatment

10. COMMENTS   Not well designed. What comes out of generator is unknown. No real controls

1. REFERENCE
    NASA SP-212

    INVESTIGATOR(S)
    W.C. Kocmond

    ORGANIZATION
    Cornell Aeronautical Laboratory, Inc.

    PUBLICATION DATE
    February 1969

    SPONSOR
    NASA

2. OBJECTIVE

    Improve Visibility

3. PHYSICAL BASIS

    Alter Drop Size Distribution

4. EXPERIMENT TYPE

    Field

5. INITIAL PARAMETERS   Drop size distribution, drop concentration, liquid water content, visibility, CCN concentration, temperature, fog depth

6. PROCESS MODE   Sized NaCl (sized by MRI), ground and aerial seeding

7. FACTORS CONSIDERED IN NUMERICAL MODELS

8. PARAMETERS AFTER TREATMENT   Visibility, drop size distribution, drop concentration, liquid water content

9. CONCLUSIONS   (1) Ground seeding can produce some improvement in visibility.   (2) Airborne seeding is more effective

10. COMMENTS   25 ground seedings and 6 aerial seedings

1. REFERENCE
   Nature

   INVESTIGATOR(S)
   Y. Mihara

   ORGANIZATION
   Div. of Meteor., Nat. Inst. Agric. Sci., Tokyo

   PUBLICATION DATE
   November 1966

   SPONSOR

2. OBJECTIVE
   Prevent frost

3. PHYSICAL BASIS
   Stabilize fog droplets

4. EXPERIMENT TYPE
   Field

5. INITIAL PARAMETERS   Composition of surface active material

6. PROCESS MODE   Spray emulsion into air

7. FACTORS CONSIDERED IN NUMERICAL MODELS

8. PARAMETERS AFTER TREATMENT   Temperature, radiation

9. CONCLUSIONS   Possible frost prevention

10. COMMENTS   Not a convincing demonstration

1. REFERENCE
NASA Contractor
Report NASA CR-2079

INVESTIGATOR(S)
W.C. Kocmond, E.J. Mack,
U. Katz and R.J. Pilie

PUBLICATION DATE
July 1972

ORGANIZATION
Cornell Aeronautical Laboratory, Inc.

SPONSOR
NASA

2. OBJECTIVE

Prevent Fog Formation

3. PHYSICAL BASIS

Deactivate CCN

4. EXPERIMENT TYPE

Large Fog Chamber

5. INITIAL PARAMETERS   Drop size distribution (coated with surface active material and then evaporated), droplet concentration, visibility

6. PROCESS MODE   Cetyl alcohol to affect evaporation and condensation rates and possibly deactivate nuclei

7. FACTORS CONSIDERED IN NUMERICAL MODELS

8. PARAMETERS AFTER TREATMENT   Drop size distribution, droplet concentration, visibility

9. CONCLUSIONS   (1) Fog formation slightly retarded.   (2) Fog dissipation significantly retarded

10. COMMENTS   An exploratory experiment that requires validation under varying experimental conditions

1. REFERENCE
NASA Contractor
Report NASA CR-1731

INVESTIGATOR(S)
W.C. Kocmond, R.J. Pilié, W.J. Eadie,
E.J. Mack and R.P. Leonard

ORGANIZATION
Cornell Aeronautical Laboratory, Inc.

PUBLICATION DATE
April 1971

SPONSOR
NASA

2. OBJECTIVES
Improve Visibility

3. PHYSICAL BASIS
Alter Drop Size Distribution

4. EXPERIMENT TYPE
Large Fog Chamber

5. INITIAL PARAMETERS Visibility, drop size distribution, drop concentration, liquid water content

6. PROCESS MODE Polyelectrolytes (sized), seeding mass (23 different materials)

7. FACTORS CONSIDERED IN NUMERICAL MODELS

8. PARAMETERS AFTER TREATMENT Visibility, drop size distribution, drop concentration, liquid water
content, time

9. CONCLUSIONS None of the materials was effective

10 COMMENTS

1. REFERENCE
Preprints Second Conf.
on Weather Modification
Santa Barbara, California

INVESTIGATOR(S)
C.L. Taylor and T. Owens

ORGANIZATION
Naval Postgraduate School

PUBLICATION DATE
April 1970

SPONSOR
Naval Weapons Center

2. OBJECTIVE
Improve Visibility

3. PHYSICAL BASIS
Alter Drop Size Distribution

4. EXPERIMENT TYPE
Small Fog Chamber

5. INITIAL PARAMETERS   Visibility

6. PROCESS MODE   Add surfactants by spray of solution

7. FACTORS CONSIDERED IN NUMERICAL MODELS

8. PARAMETERS AFTER TREATMENT   Visibility and time

9. CONCLUSIONS   Two surfactants effective

10. COMMENTS   Poorly planned and inconclusive

1. REFERENCE
   NASA SP-212

   INVESTIGATOR(S)
   W.C. Kocmond

   ORGANIZATION
   Cornell Aeronautical Laboratory, Inc.

   PUBLICATION DATE
   February 1969

   SPONSOR
   NASA

   2. OBJECTIVE
   Improve Visibility

   3. PHYSICAL BASIS
   Alter Drop Size Distribution

   4. EXPERIMENT TYPE
   Large Fog Chamber

5. INITIAL PARAMETERS   Visibility, drop size distribution, drop concentration, liquid water content

6. PROCESS MODE   Sized NaCl, $CO(NH_2)_2$, NH_4NO_3 - $CO(NH_2)_2$ - H_2O, NaH_2PO_4, Na_2HPO_4, various poly-electrolytes; seeding mass

7. FACTORS CONSIDERED IN NUMERICAL MODELS

8. PARAMETERS AFTER TREATMENT   Visibility, drop size distribution, liquid water content, drop concentration

9. CONCLUSIONS   All substances but polyelectrolytes effective

10. COMMENTS

1. REFERENCE
   J. Appl. Met.

   INVESTIGATOR(S)
   J.E. Jiusto, R.J. Pilié and W.C. Kocmond

   ORGANIZATION
   Cornell Aeronautical Laboratory, Inc.

   PUBLICATION DATE
   October 1968

   SPONSOR
   NASA

   4. EXPERIMENT TYPE
   Large Fog Chamber

2. OBJECTIVE
   Increase Visibility

3. PHYSICAL BASIS
   Alter Drop Size Distribution

5. INITIAL PARAMETERS   Average drop radius, drop size range, liquid water content, droplet concentration, visibility

6. PROCESS MODE   NaCl prepared in Cornell Particle Classifier and Disseminator, NaCl particle size distribution, particle concentration, time

7. FACTORS CONSIDERED IN NUMERICAL MODELS

8. PARAMETERS AFTER TREATMENT   Droplet size distribution, time, liquid water content, visibility

9. CONCLUSIONS   (1) Significant improvement in visibility possible.   (2) Initial fog parameters must be specified for success.   (3) Nucleant particle size must be controlled

10. COMMENTS

1. REFERENCE
NASA Contractor
Report NASA CR-1071

   INVESTIGATOR(S)
   W.C. Kocmond and J.E. Jiusto

   ORGANIZATION
   Cornell Aeronautical Laboratory, Inc.

   PUBLICATION DATE
   June 1968

   SPONSOR
   NASA

2. OBJECTIVE
   Pretreat Potential Fog

3. PHYSICAL BASIS
   Alter Drop Size Distribution

4. EXPERIMENT TYPE
   Large Fog Chamber

5. INITIAL PARAMETERS   Temperature, pressure, relative humidity

6. PROCESS MODE   Sized NaCl (in Cornell device), introduced at 95% RH

7. FACTORS CONSIDERED IN NUMERICAL MODELS

8. PARAMETERS AFTER TREATMENT   Drop size distribution, time, liquid water content, visibility

9. CONCLUSIONS   Visibility degradation less than control

10. COMMENTS

1. REFERENCE
NASA Contractor
Report NASA CR-675

INVESTIGATOR(S)
R.J. Pilié and W.C. Kocmond

ORGANIZATION
Cornell Aeronautical Laboratory, Inc.

PUBLICATION DATE
February 1967

SPONSOR
NASA

2. OBJECTIVE
Pretreat Potential Fog

3. PHYSICAL BASIS
Alter Drop Size Distribution

4. EXPERIMENT TYPE
Small Fog Chamber

5. INITIAL PARAMETERS   Visibility

6. PROCESS MODE   NaCl prepared in settling chamber to obtain desired size range

7. FACTORS CONSIDERED IN NUMERICAL MODELS

8. PARAMETERS AFTER TREATMENT   Visibility and time

9. CONCLUSIONS   (1) Degradation in visibility decreased.   (2) Overseeding can lead to poorer visibility than control.   (3) Careful control of size and number of seeding nuclei is required

10. COMMENTS

1. REFERENCE
NASA Contractor
Report NASA CR-675

INVESTIGATOR(S)
R.J. Pilié and W.C. Kocmond

ORGANIZATION
Cornell Aeronautical Laboratory, Inc.

PUBLICATION DATE
February 1967

SPONSOR
NASA

2. OBJECTIVE
Improve Visibility

3. PHYSICAL BASIS
Enhance Coalescence by Electric Field

4. EXPERIMENT TYPE
Small Cloud Chamber

5. INITIAL PARAMETERS   Fog droplet concentration and mean size

6. PROCESS MODE   Apply high voltage field

7. FACTORS CONSIDERED IN NUMERICAL MODELS

8. PARAMETERS AFTER TREATMENT   Droplet charge

9. CONCLUSIONS   With reasonable fields (up to 10^4 volts/meter) electric forces on charged particles are an order of magnitude less than gravitational forces. Hence this mode of fog dispersion is impractical

10. COMMENTS

1. REFERENCE
   J. Appl. Met.

   INVESTIGATOR(S)
   A.I. Weinstein and B.A. Silverman

   ORGANIZATION
   AFCRL

   PUBLICATION DATE
   August 1973

   SPONSOR
   AFCRL

   4. EXPERIMENT TYPE
      Numerical

2. OBJECTIVE
   Improve Visibility

   3. PHYSICAL BASIS
      Alter Drop Size Distribution

5. INITIAL PARAMETERS Temperature, pressure, turbulent diffusion coefficient, fog depth, liquid
   water content, visibility, drop size distribution

6. PROCESS MODE (1) NaCl (known particle size distribution), (2) monodispersed urea, (3) urea
   (known size distribution, (4) seeding pattern

7. FACTORS CONSIDERED IN NUMERICAL MODELS Condensation and evaporation, drop fallout, turbulent and
   advactive transport

8. PARAMETERS AFTER TREATMENT Relative humidity, liquid water content, visibility, time

9. CONCLUSIONS (1) Single line seeding valueless. (2) Nucleant particle size must be controlled.
   (3) Cost estimate given. (4) Targeting problem discussed

10. COMMENTS Assumes constant temperature, no coalescence. Cost estimate as of publication time

1. REFERENCE
Preprints Third Conf.
on Weather Modification
Rapid City, S.D.

INVESTIGATOR(S)
R.D. Chu and S.D. Thayer

ORGANIZATION
GEOMET, Inc.

PUBLICATION DATE
June 1972

SPONSOR
ONR

2. OBJECTIVE
Improve Visibility

3. PHYSICAL BASIS
Alter Drop Size Distribution

4. EXPERIMENT TYPE
Numerical

5. INITIAL PARAMETERS   Fog depth, fog droplet size, liquid water content, droplets assumed nucleated
on NaCl 0.1 micron, temperature, relative humidity, total pressure, visibility

6. PROCESS MODE   Monodisperse salt particles (20 microns), time

7. FACTORS CONSIDERED IN NUMERICAL MODELS   Condensation and evaporation, change of supersaturation with
time, latent heat, turbulent and advective transport, sedimentation

8. PARAMETERS AFTER TREATMENT   Droplet concentration, liquid water content, visibility, time

9. CONCLUSIONS   (1) Advection and wind shear decrease effectiveness.   (2) Rate of evaporation depends
on initial CCN size and composition

10. COMMENTS

1. REFERENCE
   Proceedings Int. Conf.
   on Weather Modification
   Canberra, Australia

   INVESTIGATOR(S)
   B.A. Silverman, A.I. Weinstein,
   C-W Chien and L.D. Nelson

   ORGANIZATION
   AFCRL and MRI

   PUBLICATION DATE
   September 1971

   SPONSOR
   AFCRL

2. OBJECTIVE

   Improve Visibility

3. PHYSICAL BASIS

   Alter Drop Size Distribution

4. EXPERIMENT TYPE

   Numerical

5. INITIAL PARAMETERS   Pressure, temperature, relative humidity, fog depth, liquid water content,
   drop size distribution

6. PROCESS MODE   Urea of known particle size

7. FACTORS CONSIDERED IN NUMERICAL MODELS   Condensation and evaporation, fallout, turbulent and
   advective diffusion

8. PARAMETERS AFTER TREATMENT   Visibility

9. CONCLUSIONS   (1) Turbulent diffusion and vertical wind shear both greatly reduce seeding effectiveness.
   (2) Doubling seeding rate improves matters

10. COMMENTS   Do not consider heat of solution of urea

1. REFERENCE
NASA Contractor
Report NASA CR-1731

INVESTIGATOR(S)
W.C. Kocmond, R.J. Pilié, W.J. Eadie,
E.J. Mack and R.P. Leonard

PUBLICATION DATE
April 1971

ORGANIZATION
Cornell Aeronautital Laboratory, Inc.

SPONSOR
NASA

2. OBJECTIVE
Improve Visibility

3. PHYSICAL BASIS
Alter Drop Size Distribution

4. EXPERIMENT TYPE
Numerical

5. INITIAL PARAMETERS   Fog depth, drop size (monodisperse), drop concentration, nature of CCN, visibility, liquid water content, turbulent diffusion coefficient

6. PROCESS MODE   Monodisperse NaCl particles

7. FACTORS CONSIDERED IN NUMERICAL MODELS   Condensation and evaporation, change in supersaturation, turbulent transport, sedimentation

8. PARAMETERS AFTER TREATMENT   Vertical visibility, horizontal visibility, liquid water content

9. CONCLUSIONS   (1) Turbulence can strongly affect seeding effectiveness.   (2) More data on such turbulence required

10. COMMENTS

1. REFERENCE   INVESTIGATOR(S)   PUBLICATION DATE
    Monthly Weather Review   L.R. Koenig   March 1971

                                         ORGANIZATION   SPONSOR
                                         Rand Corp.   USAF

        2. OBJECTIVES   3. PHYSICAL BASIS   4. EXPERIMENT TYPE

        Improve Visibility   Alter Drop Size Distribution   Numerical

5. INITIAL PARAMETERS   Temperature, pressure, CCN distribution, constant cooling rate

6. PROCESS MODE   (1) Forms fog on CCN, (2) seeds with NaCl (known size distribution and concentration)

7. FACTORS CONSIDERED IN NUMERICAL MODELS   Evaporation and condensation, sedimentation

8. PARAMETERS AFTER TREATMENT   Visibility and supersaturation ratio

9. CONCLUSIONS   (1) Visibility may be improved.   (2) Effect of various inputs on process rates.
    (3) Best effects with monodisperse NaCl (but effect is short-lived).   (4) Microphysical properties
    of fog less important than depth of fog

10. COMMENTS   Model validated (?) by comparison with experiment as reported by others

1. REFERENCE
   J. Appl. Met.

   INVESTIGATOR(S)
   B.A. Kunkel and B.A. Silverman

   PUBLICATION DATE
   August 1970

   ORGANIZATION
   AFCRL

   SPONSOR
   AFCRL

   2. OBJECTIVE

      Improve Visibility

   3. PHYSICAL BASIS

      Alter Drop Size Distribution

   4. EXPERIMENT TYPE

      Numerical

5. INITIAL PARAMETERS   Temperature, pressure, drop size distribution, liquid water content, visibility, fog depth

6. PROCESS MODE   Variety of materials with 50 micron particle size, particle concentration or mass dispensing rate

7. FACTORS CONSIDERED IN NUMERICAL MODELS   Condensation, evaporation and coalescence

8. PARAMETERS AFTER TREATMENT   Visibility

9. CONCLUSIONS   (1) Droplet formed on hygroscopic particle should retain as low as possible water vapor pressure.   (2) High density desirable at constant flow volume flow rate.   (3) Low density desirable if seeding is on total mass basis.   Order of effectiveness: hydroxides, chlorides, bromides, nitrates, iodides and sulfates

10. COMMENTS   Simple model

1. REFERENCE
   J. Appl. Met.

   INVESTIGATOR(S)
   B.A. Silverman and B.A. Kunkel

   ORGANIZATION
   AFCRL

   PUBLICATION DATE
   August 1970

   SPONSOR
   AFCRL

2. OBJECTIVE

   Improve Visibility

3. PHYSICAL BASIS

   Alter Drop Size Distribution

4. EXPERIMENT TYPE

   Numerical

5. INITIAL PARAMETERS   Temperature, pressure, relative humidity, drop size distribution, liquid water content, visibility

6. PROCESS MODE   Monodisperse NaCl mass and time

7. FACTORS CONSIDERED IN NUMERICAL MODELS   Condensation and evaporation, coalescence, sedimentation

8. PARAMETERS AFTER TREATMENT   Vertical and horizontal visibility

9. CONCLUSIONS   (1) Seeding can be useful.   (2) 10 micron particles most efficient.   (3) Coalescence becomes significant with increasing fog depth

10. COMMENTS   Simple model.   Assumes coalescence efficiency of unity.

1. REFERENCE
J. Appl. Met.

INVESTIGATOR(S)
P. Kornfeld

ORGANIZATION
NCAR

PUBLICATION DATE
June 1970

SPONSOR
NSF

2. OBJECTIVE
Improve Visibility

3. PHYSICAL BASIS
Alter Drop Size Spectrum

4. EXPERIMENT TYPE
Numerical

5. INITIAL PARAMETERS   Temperature, pressure, liquid water content, drop size distribution, CCN distribution (assumed NaCl), relative humidity, visibility

6. PROCESS MODE   NaCl, $MgCl_2$ and BeF_2 (known size distribution), particle concentration, time

7. FACTORS CONSIDERED IN NUMERICAL MODELS   Condensation and evaporation, latent heat

8. PARAMETERS AFTER TREATMENT   Visibility, drop size distribution

9. CONCLUSIONS   (1) Effect depends on initial drop size distribution.   (2) Some fallout is desirable

10. COMMENTS   Simple model with forseeable conclusions

1. REFERENCE
Preprints Second Conf.
on Weather Modification
Santa Barbara, California

INVESTIGATOR(S)
B.A. Silverman

ORGANIZATION
AFCRL

PUBLICATION DATE
April 1970

SPONSOR
AFCRL

2. OBJECTIVE

Improve Visibility

3. PHYSICAL BASIS

Alter Drop Size Distribution

4. EXPERIMENT TYPE

Numerical

5. INITIAL PARAMETERS   Temperature, relative humidity, liquid water content, fog depth, visibility, fog droplet size spectrum

6. PROCESS MODE   Sized NaCl particles (single distribution in size), particle concentration, time

7. FACTORS CONSIDERED IN NUMERICAL MODELS   Condensation and evaporation, sedimentation, turbulent diffusion

8. PARAMETERS AFTER TREATMENT   Visibility, liquid water content, relative humidity, time

9. CONCLUSIONS   (1) Visibility improved.   (2) Turbulence decreases visibility improvement

10. COMMENTS   Two dimensional model

1. REFERENCE
Preprints Second Conf.
on Weather Modification
Santa Barbara, California

INVESTIGATOR(S)
B.A. Silverman and T.B. Smith

ORGANIZATION
AFCRL and MRI

PUBLICATION DATE
April 1970

SPONSOR
AFCRL

2. OBJECTIVE
Visibility Improvement

3. PHYSICAL BASIS
Alter Drop Size Distribution

4. EXPERIMENT TYPE
Numerical

5. INITIAL PARAMETERS   Pressure, temperature, fog depth, liquid water content, turbulent diffusion coefficient

6. PROCESS MODE   Sized NaCl particles (size range), mass concentration, time

7. FACTORS CONSIDERED IN NUMERICAL MODELS   Condensation and evaporation, sedimentation, turbulent transport

8. PARAMETERS AFTER TREATMENT   Liquid water content, relative humidity, time

9. CONCLUSIONS   Confidence in utilizing important factors in model

10. COMMENTS   Model not presented in detail

1. REFERENCE
Preprints Second Conf.
on Weather Modification
Santa Barbara, California

PUBLICATION DATE
April 1970

INVESTIGATOR(S)
P.M. Tag, D.B. Johnson
and E.E. Hindman II

ORGANIZATION
Naval Weather Research Facility

SPONSOR
Navy

2. OBJECTIVE
Improve Visibility

3. PHYSICAL BASIS
Alter Drop Size Distribution

4. EXPERIMENT TYPE
Numerical

5. INITIAL PARAMETERS   Temperature, pressure, relative humidity, fog droplet size distribution, drop concentration, salt concentration in droplets, visibility

6. PROCESS MODE   Sized droplets of water-NH_4NO_3-urea (size ranges, median mass radius, number density, solute concentration), time

7. FACTORS CONSIDERED IN NUMERICAL MODELS   Condensation and evaporation, coalescence, sedimentation, vertical turbulent mixing

8. PARAMETERS AFTER TREATMENT   Visibility, time

9. CONCLUSIONS   (1) Seeding droplet sizes must be controlled.   (2) The effect of height at which the nucleant is introduced is considered

10. COMMENTS   Model is one-dimensional (height), no horizontal advection or diffusion is permitted

1. REFERENCE
NASA SP-212

INVESTIGATOR(S)
W.J. Eadie

PUBLICATION DATE
February 1969

ORGANIZATION
Cornell Aeronautical Laboratory, Inc.

SPONSOR
NASA

2. OBJECTIVE

3. PHYSICAL BASIS

4. EXPERIMENT TYPE

Improve Visibility

Alter Drop Size Distribution

Numerical

5. INITIAL PARAMETERS   Fog drop size distribution, size and nature of CCN, visibility

6. PROCESS MODE   Sized NaCl addition (size distribution), quantity added

7. FACTORS CONSIDERED IN NUMERICAL MODELS   Condensation and evaporation, change of supersaturation with time, latent heat, sedimentation

8. PARAMETERS AFTER TREATMENT   Visibility, relative humidity, time

9. CONCLUSIONS   (1) Describe tradeoffs in nucleant mass versus target effectiveness.   (2) Important role of computer simulation discussed

10. COMMENTS   One-dimensional model. No turbulence or wind effects. Somewhat unrealistic

PUBLICATION DATE
June 1968

SPONSOR
NASA

1. REFERENCE
NASA Contractor
Report NASA CR-1071

INVESTIGATOR(S)
W.C. Kocmond and J.E. Jiusto

ORGANIZATION
Cornell Aeronautical Laboratory, Inc.

3. PHYSICAL BASIS
Alter Drop Size Distribution

4. EXPERIMENT TYPE
Numerical

2. OBJECTIVE
Improve Visibility

5. INITIAL PARAMETERS Temperature, fog depth, fog drop radii, liquid water content, visibility, relative humidity

6. PROCESS MODE Monodisperse NaCl, particle concentration

7. FACTORS CONSIDERED IN NUMERICAL MODELS Condensation and evaporation, fall time of droplets growing on seed

8. PARAMETERS AFTER TREATMENT Drop size distribution, visibility and time

9. CONCLUSIONS (1) Points out tradeoffs. (2) Sized seed essential

10. COMMENTS Very simple model

2.7 Summary of Fog Modification Experiments

The great bulk of experiments in simulated fog chamber and in the field as well as the greatest modelling efforts have been made by three organizations (1) the Cornell Aeronautical Laboratory under the sponsorship of NASA, (2) The Air Force Cambridge Research Laboratories under the sponsorship of the Air Force and (3) The Naval Weapons Center at China Lake. There are thus only three research groups active in this area.

The major thrust is toward an increase in visibility primarily through the route of fog droplet size distribution modification. There is little effort in fog stabilization or fog prevention through poisoning of condensation nuclei.

Fog dissipation through alteration in the fog droplet size distribution works in the laboratory and in simulated models based on laboratory conditions. There is little doubt that the basic concept is correct; i.e., a change in droplet size distribution toward larger particles brought about by the introduction of hygroscopic nuclei and the corresponding decrease in light scattering.

Field experiments, however, introduce additional variables. The dynamic nature of the process can be affected by uncontrollable ambient conditions including loss of treated droplets or nuclei through turbulent or advective transport. There is evidently some difficulty in assuring that the hygroscopic seeds ever reach the desired target area.

The quality of the experiments is variable. Some, however, are carefully designed and conducted and the results may be considered significant. The experiments definitely rule out as effective drop size distribution changes brought about by electric field or particle charging with polyelectrolytes. It is, however, not clear that polyelectrolytes may be ruled out in a swelling mode; no experiments have been designed to test this possible effect.

It is clear that in the laboratory or numerical simulation the addition of hygroscopic nuclei to a warm fog under controlled conditions will bring about an alteration in droplet size distribution and an improvement in visibility. This is a dynamic process and some of the details are not clearly understood. Questions that may be asked include the following.

(1) Are the available growth equations valid for the formation of a droplet of liquid solution from the solid nucleant and water vapor?

(2) Are the growth equation valid for the growth of this drop?

(3) What effect do surface active agents have on droplet growth or evaporation?

(4) What is the nature of the coalescence effect and what bearing does this effect have on the dynamic alteration in particle size distribution?

(5) How are the properties of the fog affected by the CCN originally leading to fog formation?

(6) How effectively may CCN of varying chemical composition be "poisoned"?

(7) What substances, if any, are effective poisons?

(8) Will surface active materials in the natural environment (polluted atmospheres) act to stabilize warm fogs?

In the field or numerical simulation of field experiments the additional effects of atmospheric transport must be considered in terms of turbulent or advective diffusion. The results obtained in the field are far less conclusive with respect to fog dissipation than the laboratory experiments. Targetting seems a major problem. These problems are considered in more detail in Chapter 3.

One further question may be considered regarding the possible use of polyelectrolytes by a "swelling" rather than electrostatic mode. The joint use of polyelectrolytes and hygroscopic salts might be effective.

In the area of instrumentation a crying need is the development of a capability of measuring supersaturation ratios with an effective resolving time on the order of a second or less. CCN counting seems adequate. The chemical nature of natural CCN deserves considerable attention; hygroscopic characteristics are almost unknown. The determination of the size of fog droplets at diameters below one micron is presently unsatisfactory.

2.8 References

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Chapter 3

TURBULENCE AND AIRFLOW

3.1 Introduction

It is now rather widely believed that turbulence is essential to
the formation and maintenance of most fog (U.S. Navy, 1974). The air-
flow and turbulence aspects of fog physics (or of fog control) are
closely related but are treated separately in this report because of
some distinct differences in problems due to each of these two aspects
of air motion.

The nonturbulence component of air motion, here designated as the
airflow, exhibits variation in space and time in the following ways
which have major significance for fog.

1. Trajectories for larger fog masses are not adequately
    predictable for periods greater than 5 to 10 minutes for
    scales less than mesoscale (Appleman, 1969).

2. Trajectories for fog parcels may vary with height due to
    vertical shear of wind velocity (Kocmond, personal communica-
    tion, 1974).

3. Turbulence characteristics of fog are strongly influenced by
    the wind shear and static stability of the airflow and by the
    interaction of the airflow and the surface of the earth.

4. Modification of the effect of turbulent diffusion in
    determining the concentration of airborne particulates.

The nonturbulence air motion problem primarily affects modification
efforts and must be treated in terms of improved measurement and local
prediction capability. This is discussed in sections 3.10 and 3.11.

Turbulence strongly influences the processes of:

1. Water vapor saturation thermodynamics and kinematics, (Fukuta
    and Saxena, 1973).

2. Fog particle nucleation, growth and coalescence (e.g. Tennekes
    and Woods, 1973).

3. Advertent modification of fog (Kocmond, personal communication,
    1974).

Specific examples of observed or inferred turbulence influences on fog
processes are cited in subsequent sections.

Some data on fog and turbulence properties are presented for
orientation purposes in Table A-4 only as order of magnitude estimates
of some rates and intensities of importance in fog physics (Table A-6).

A few additional pieces of such information, related to turbulence effects on microphysical processes, are presented in Table 3.1 to aid in evaluation of the importance of processes to be discussed in the rest of this chapter. For similar reasons the basic ways in which fog may form are stated again but differently than in Appendix A and are discussed in greater detail in the next paragraph of this section.

An air parcel which is foggy may have acquired the water droplets by one or several of the following means.

1. Droplet settling or injection.

2. Mixing transport of droplets by turbulence.

3. Condensation of water vapor on nuclei:

    (a) Without an initiating change in either the water vapor content, χ_v, or the saturation mixing ratio over plane water, χ_s.

    (b) By increase in χ_v.

    (c) By decrease in χ_s.

Process 3 requires some additional discussion. Process 3a occurs when proper nucleants are introduced into the volume either by a settling-injection process or by mixing. Process 3b may occur in four ways:

1. Injection and subsequent evaporation of liquid.

2. Molecular diffusion of water vapor.

3. Turbulent transport of water vapor.

4. Chemical reactions, e.g., organic combustion and recovery of temperature.

Process 3c may occur in two basic ways:

1. Reduction of actual equilibrium vapor pressure by hygroscopic nuclei.

2. Reduction of equilibrium vapor pressure relative to plane water by decreasing the temperature of the air containing the water vapor using the following mechanisms:

    (a) Turbulent mixing in of cooler air.

    (b) Molecular diffusion of heat from air.

    (c) Radiation cooling of air.

    (d) Evaporation of acquired water.

TABLE 3-1

A Few Estimated Data Related to Turbulence Effects on Microphysical Processes

Mean free path for water vapor molecules in a saturated environment:	$\lambda \sim 10^{-1}$ μm
Growth of a 10 μm droplet approaches steady state conditions in	$\Delta t = 10^{-4}$ sec
Diffusional growth interaction for droplet pair is significant only if	$\dot{r}_1 \doteq \dot{r}_2$
Spatial extent of diffusional profiles around a 1-10 μ droplet is	$r = 5 \rightarrow 20$ μm
Droplet separation for a number depth of n = 500 cm^{-3}:	$\Delta r \sim 780$ μm
Terminal fall speed of a 40 μ droplet:	$v_t \doteq 4$ cm s^{-1}
Time required for small droplets to reach terminal fall speed:	$\Delta t \sim 10^{-3}$ sec
Shears over regions of ~ 1 mm which enhance droplet coalescence:	$\dfrac{\partial v}{\partial z} > 7$ s^{-1}
Shear of mean wind in fog:	$\dfrac{\partial v}{\partial z} = 0 \rightarrow 0.015$ s^{-1}
Turbulent diffusion coefficient very near droplets:	$D \sim 10^{-9}$ m^2 s^{-1}
Turbulent transport coefficients in fog flow field:	$K_m \doteq 0.1 \rightarrow 10$ m^2 s^{-1}
Cooling rate for a marine fog (observed)	$\dfrac{\partial T}{\partial t} \doteq 1 \rightarrow 3$ C hr^{-1}
Radiation cooling rate for fog air (calculated):	$\dfrac{\partial T}{\partial t} \sim 1$ C hr^{-1}

(e) Conduction to cooler acquired matter.

(f) Expansion cooling.

   1. Lifted parcel.

   2. Horizontal motion to lower atmospheric pressure.

It is apparent that several mechanisms are likely to be operative simultaneously and/or sequentially and unobserved. The understanding of the importance of turbulent fluctuations of air motion depends upon controlling and understanding the significance of other processes in both their mean and turbulent aspects.

3-2 Significant Gaps in Fog Knowledge and Some Important Questions
     about Fog Turbulence

   Reference may be made to a number of reports, papers and books for descriptions of fog properties and classifications of fog types. (Table A-4 contains a list of fog properties and estimated observed or inferred values for some of the properties. The table is not the result of a comprehensive compilation and is intended only for qualitative and rough quantitative purposes.) Several important omissions are apparent in the information found in these sources.

   1. The relative importance of different processes for producing
       specific fogs is not well known and in some situations is not
       known at all.

   2. Time and spatial variations of important fog parameters and
       immediately-prefog characteristics of the atmosphere seldom
       have been measured.

   3. Turbulence of the air motion and other properties in and
       around fog are almost never directly measured. Thus the
       importance of turbulent transports and other physical eddy
       cross correlations must be inferred from observations of mean
       states which may result from several processes.

   Within the scientific and fog-operations communities opinion is growing toward a consensus that turbulence is of considerable importance in determining the thermodynamical and microphysical effects. The following set of questions is used in this chapter as a guide to the evaluation of turbulent effects in fog science and technology.

   1. For what physical processes in fog is turbulence important?

   2. What microphysics research is required because of turbulence
       effects?

   3. What do we know about fog turbulence?

   4. What do we need to know about fog turbulence?

   5. How can the required knowledge be achieved?

   6. What can be learned by chamber, wind tunnel and numerical
       simulations?

7. What important observations of turbulent processes must be made in real atmospheric fog?

8. How do other processes confuse indirect methods of estimating the effect of turbulence?

9. How important is the direct and concurrent measurement of turbulence properties of the air motion and the microphysics?

10. How may the required measurements be made?

If questions such as these can be correctly answered, a reasonable set of research priorities can be set for gaining much needed knowledge about fogs. Such research seems to hold the promise of a distinctly higher level of optimization of fog control. The topic of each of these questions is discussed in the subsequent sections of the present chapter.

3.3 Turbulence and Fog Generation and Dissipation

3.3.1 Examples of Effects of Turbulence

It is commonly observed that when a hole is cleared in fog by any method, fog is observed to refill the volume from the edge of the cleared volume in a turbulent manner. Rodhe (1962) demonstrated that turbulent mixing is required for the existence of any fog which is more than a few meters thick. Although radiation cooling can be quite strong, weak turbulence transports heat so rapidly as to dominate radiation effects in many cases. Rodhe used an analytic improvement of a graphical method for estimating the effect of mixing of heat and water vapor to achieve saturation. Pilié (1966) reported results of a mathematical model which added analytical expressions for boundary layer profiles of wind and temperature to Rodhe's model. The roughness of the underlying surface determined the height to which significant mixing-cooling and thus maximum liquid water content would exist.

More recent models of fog have represented turbulence more explicitly in terms of airflow. Weinstein and Silverman (1973) used a model in which turbulent mixing was parameterized by an eddy coefficient, $K_m (= 1$ to 10 m^2 s^{-1}), and a vertical gradient of wind speed, $\partial v/\partial z (= 0$ to 0.01 s^{-1}). Turbulence effects were significant even though it would be difficult to measure the atmospheric wind shear magnitudes which were modeled and found to be important.

Pepper and Lee (1973) utilize a finite difference solution to planetary boundary layer equations into which turbulent transports, radiation, wet thermodynamics and fog microphysics are incorporated. Exchange coefficients are held constant and eddy transports are proportional to kinetic energy of turbulence and to the ratio of the gradient of property to the gradient of the mean wind speed. Maximum liquid water concentration remains near the cooler sea surface. A sequence evolves in which radiation eventually cools the air until it suppresses further moisture flux from the surface and the fog layer lifts. The maximum height of fog tops is lower for higher wind speeds.

Fukuta and Saxena (1974) performed a theoretical analysis of airflow over a moist cold plate which showed that a supersaturation wave propagates upward from the plate by molecular transport processes if the rates of transport processes if the rates of transport of water vapor and heat are not identical. On the basis of this result they showed that

1. Fog forms in both stable and unstable stratification and

2. Molecular transports at the underlying surface may sometimes limit the effective turbulent transport rates in the air mass and thereby control fog formation and dissipation.

Hidy (see Fukuta and Saxena, 1973) performed an analysis of the effect of different coefficients of turbulent exchange for heat and water vapor. Hidy concluded that if the coefficients are equal then the greatest possible chance exists that mixing will result in supersaturation.

Kinzer and Cobb (1958) compared their laboratory observations with theory for droplet coalescence. They concluded that larger collector droplets create a turbulent airflow near themselves which moves small droplets randomly (about 0.5 mm s^{-1}) at least an order of magnitude greater than can be explained by Brownian (molecular collision-induced) motion. This motion diffuses small cloud droplets closer to the collector drop. Thus inertial collisions are enhanced. The electrostatic enhancement of coalescence is also increased since the electrostatic force is effective only when droplet surfaces are separated by less than about 3 μm.

Greatly enhanced rates of coagulation of micron-size solid have been produced by very modest levels of turbulence (Green and Lane, 1964).

Saffman and Turner (1955) developed a collision theory incorporating turbulence and concluded that significant effects would be found only for nonlayered clouds. However, Woods et al. (1972) proposed that the principal factor is the strong spectral peak of shear on the scale of the Kolmogoroff microscale. Jonas and Goldsmith (1972) showed experimentally that droplet collision efficiency increases markedly beyond a threshold shear of 7 sec^{-1}. Using these observations and considering non-normal distribution of shear Tennekes and Woods (1973) show that coalescence is greatly enhanced in weakly turbulent clouds.

The discussion in this section has so far related to velocity turbulence. Many other properties of fog may experience fluctuations which may be significant. Kunkel (1971) showed that there were large time-dependent variations in droplet concentration, size spectrum characteristics and liquid water content in real fog (see Fig. A-7). Rogers, Mack and Pilié (1972) also measured significant variations in droplet spectra for small time scales (see Fig. A-6). Variations in space and time on larger scales of liquid water characteristics of fog have been observed by Rogers, Mack and Pilié (1972) (see Fig. A-8) and by Okita (1962) (see Fig. A-5).

K, whose magnitude was up to $0.2 \, m^2 \, s^{-1}$. Their conclusion was that when K is largest at the top of the fog, droplet density decreases. Variable supersaturation near the top controlled droplet growth much more than did variable supersaturation in the body of the fog.

3.3.2 An Elementary Model of the Mixing Process for Water Vapor Saturation

Mixing of fog air occurs by motions of air elements of all sizes from about 1 mm to several hundred meters. The greatest contribution to the total transport of properties generally occurs at intermediate size eddies. The final steps toward uniformity of properties of an air mass obviously are due to the smaller eddies.

Three states of turbulent fog must be considered.

1. The average resultant state.

2. The variations of the resultant state from the average.

3. The individual-eddy states in which the microphysical processes occur.

The results in each state depend upon the details of the air mass mixing and the distribution of the properties which are mixed. For example two subsaturated parcels at different temperatures begin to mix to produce an intermediate temperature and water content. The water concentration may vary considerably over the volume, $V_1 + V_2$, of the mixing parcel pair but finally becomes a linear average of the initial two parcel values numerically weighted according to the volume of each of the parcels.

$$\bar{\chi} = \frac{V_1 \chi_1 + V_2 \chi_2}{V_1 + V_2} \quad . \tag{3.1}$$

The temperature also approaches the same type of average value except for a modification if part of the water content, χ, undergoes a change of phase. Then the function

$\bar{\chi} \, (\bar{T})$ is nearly linear.

$$\bar{\chi} = k_1 \, (\Delta \bar{\chi}, \, \Delta \bar{T}) \, \bar{T} \, . \tag{3.2}$$

However the curve for which $\chi(T)$ is always $\chi_s(T)$ is nonlinear and exponential

$$\chi_s = k_2 \, \chi_{s_o} \, e^{\frac{L}{R_v} \frac{1}{T}} \tag{3.3}$$

Then supersaturation (and potential condensation), $\bar{\chi} - \chi_s > 0$, may develop by mixing of subsaturated parcels. Similarly, mixing of a supersaturated parcel with an unsaturated parcel may increase or

decrease $\bar{\chi}$ from the initially highest saturation level (see Fig. 3-1). However, the weighting of the average for any set of mixing parcels depends upon the relative volumes of each type of air and the intensity of turbulent mixing as a function of time and space. A wide variety of sub- and supersaturation distributions are possible for mixing layers of the atmosphere.
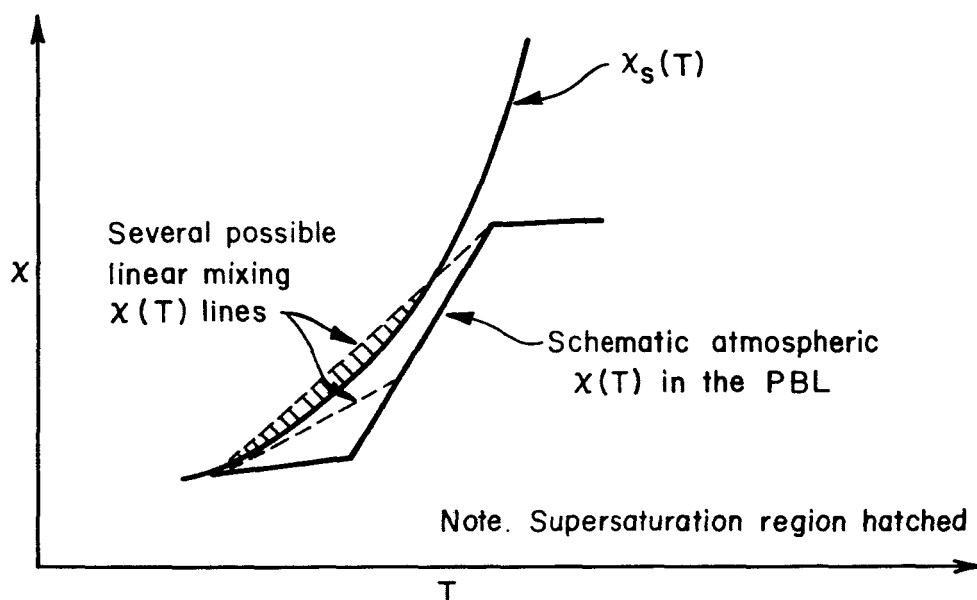

Fig. 3-1. Schematic examples of the alteration of relative humidity produced by turbulent mixing of air parcels.

It is clear that turbulence can be an important factor in fog. It is some details of the turbulence and its distribution rather than the mere existence of turbulence which determine its contribution to fog processes. An extension of the above analysis shows that time variations in environmental profiles of temperature and water vapor mixing ratio, χ_v, as well as in turbulence generation can be important in fog physics. Thus changes in surface properties and differential advection may play strong roles.

3.4   Turbulence and Fluctuation Microphysics

3.4.1 Cross Correlations and Nonlinear Microphysics Processes

Turbulent mixing produces time-varying concentrations of atmospheric and fog properties not necessarily all in the same functional way. For example, condensation nuclei may be increased in a certain volume while the water vapor and temperature may individually vary in different

directions or percentage magnitudes. Simultaneously the eddy velocity field may change so that accelerations may alter rates of those processes which are dependent upon close approach to or collision between droplets. A few relevant observations are discussed in the next subsection.

Whatever the physical processes may be, the growth rate of a given particle must exhibit fluctuations. The particle radius is a function of many factors; for example, it may be that

$$\frac{dr}{dt} \equiv \dot{r} = f \ (\chi_v, \ \chi_e, \ \overline{r}_{population}, \ \overline{w}, \ \text{nucleus spectrum}$$

and the ionic concentration of the solute).

Since all of the "independent" variables in f may fluctuate as well as interrelate in nonlinear ways; we may write symbolically

$$\dot{\overline{r}} = f_1 \ (\overline{\xi_i}) + f_2 \ (\overline{\xi_i' \ \xi_j'}) + f_3 \ (\xi_i' \ \xi_j' \ \xi_k') \ ..., \tag{3.4}$$

where ξ_i is the set of independent variables and $\xi_i = \overline{\xi} + \xi'$ with $\overline{\xi_i}$ the average state and ξ_i' the fluctuating state of the variable ξ_i.

It remains to be determined which of the eddy cross correlations may be important for droplet growth. Three examples of coalescence enhancement by eddy fluctuations were cited in section 3.3.1. Telford (1955) has shown that growth equations which consider a typical droplet coalescence in a population, not necessarily due to turbulence, provide for much more rapid modification of the diameter spectrum. Tennekes and Woods (1973) discuss a recently discovered mechanism of coalescence by turbulence (Woods, et al., 1922). The author is not aware of other specific analyses of fluctuation cross correlation contributions to the microphysics.

3.4.2 Some Scales Related to the Importance of Fluctuating and Transient Microphysics

Particle influence regions and relative motions and separations determine the significance and exact nature of many microphysical processes. A few hypothetical examples are discussed below based upon a few observed facts.

Carstens, Williams and Zung (1970) computed diffusional growth of droplets including effects of droplet-droplet growth interaction. Some input and output of their work follows. The mean free path of water vapor molecules was about 0.1 μm. Growth of a 10 μ droplet attained quasi steady state in 10^{-4}s. The spatial extension from the droplet surface of diffusional profiles was about 5-20 μm for 1-10 μm diameter droplets. Thus pairs interacted if their separation was less than about 40 μm. For $n = 500$ cm^{-3} the average droplet separation was ~780 μm and there were 0.034 pairs cm^{-3}. Between the pairs the water vapor density retained a fairly high density and it heated up significantly. It should be noted that pair growth interaction was only significant for nearly equal radii.

Without further data one would suppose that any turbulent process which could bring droplets closer together so as to share separations of less than about 40 microns could be important. Nonsteady state conditions must be considered for relative speeds greater than ~40 cm s^{-1} or for very close passages.

Turbulent eddies can accelerate local air motion and thus produce changes in relative velocities of different size droplets.

$$V_{terminal} \doteq \frac{ad^2}{18\eta} \rho = k \; a \; d^2 \qquad (3.5)$$

where a is total acceleration, d is droplet diameter and k is a constant. An eddy may change acceleration by

$$V^2/r \doteq \frac{(0.5 \; m/s)^2}{0.1 \; m} \doteq 2.5 \; m^2/sec \doteq 0.25 \; g \; \therefore \; max \; \frac{\Delta V \; terminal}{V \; terminal} = \pm 0.25$$

$$(3.6)$$

A 40 μ droplet has a terminal fall speed of about 4.0 cm s^{-1} and acceleration due to turbulence may change this by $\Delta V = \pm 0.25 \times 4.0 = 1.0$ cm s^{-1} while changing a 10 μ droplet's speed from about .25 cm s^{-1} by $\Delta V = 0.06$ cm s^{-1}. The net change in relative velocity is ~0.9 cm s^{-1}. Terminal velocities are approached within ~ 10^{-3} sec for small droplets in air. Lifetimes of single eddies are of the order of r/v = 0.2 sec. Then the relative motion between a 40 μ and a 10 μ droplet is ~40 cm/sec x 0.2 sec = .8 cm during the half period of an 0.1 m eddy having an rms speed of about 0.5 m/sec.

There is a reasonable possibility that accelerations in fog could modify the droplet spectrum by both diffusion and coalescence growth.

3.5 Required Information About Fog-Related Turbulence

A list of specific needed information is provided in Table 3-2. Column two lists how the needed information may be useful. Column three contains a priority rating (in which 1 is the highest). The best methods of obtaining the information are discussed in subsequent sections. Again, the orientation is toward understanding fog processes as a guide to learning what technology to develop.

3.6 Methods of Obtaining Needed Information about Turbulence: an Overview

The requirement is to obtain information for processes which are sufficiently like those important to real fog processes and to be able to interpret it in an unambiguous way. This implies being able to encounter or simulate the correct fog conditions, to control or understand the effect of interfering factors and to properly measure or infer the process under study. In principle direct observation of fog processes is most suitable. However, the encounter with the correct conditions and the control and understanding of interfering effects can be inadequate for many reasons of scale, instrumentation, logistics and economics. As a result a variety of simulation methods can be usefully

TABLE 3-2

Information Which Must Be Learned About Fog-Related Turbulence

Information needed	Benefit of having the information	Acquisition Priority	
Eddy flux of momentum, $\rho\,\overline{u'w'}$ (1) just above molecular boundary (2) as a function of height (3) prefog, fog, post fog states	Most reliably obtained direct measure of eddy transport of a property over wide range of scales. Estimation of eddy flux of other properties derivable. Permits realistic modeling of eddy fluxes.	(1) (2) (3)	3 1 2
Eddy flux/water vapor and heat, $\overline{w'\chi'}$. (1) just above molecular boundary (2) as a function of height (3) prefog, fog, post fog states	Direct measures permit check of K_M/K assumptions used to get $\overline{w'\chi'}$ indirectly from $\overline{u'w'}$.	(1) (2) (3)	3 2 2
Flux intensities vs eddy size (Flux Spectra)	Size of eddies by which mean profiles are dominantly controlled.		3
Turbulence anistropy	Modeling improvement.		2
Validity of eddy exchange coefficient $$w'\chi' = K_\chi \frac{\partial\chi}{\partial z}$$ (1) Is there only one cause of $\frac{\partial\chi}{\partial z}$? (2) What is $K_\chi\,(x,y,z)$?	Improved numerical modeling. Improved interpretation of field observed mean profiles.		1
Parameterization of eddy transport ($\frac{\partial\chi}{\partial z}$, i, L) (1) stable stratification (2) unstable + neutral stratification	More reliable prediction through improved parameterization of numerical models.	(1) (2)	1 3
Importance, mechanisms of turbulence generation in fog (1) roughness (2) thermal conduction and water vapor buoyancy (3) evaporation colling negative buoyancy (4) wind shear (5) radiation variations	Improved generalized turbulent transport parameterization. Improved representation of time dependence of mixing.		2
Water vapor, droplet and aerosol variations in fog (1) space (2) time	Realistic incorporation of known microphysics into fluctuation growth dynamics. Guide to need for study of nonequilibrium and fluctuation microphysics.		1
What scales and intensities of turbulence fluctuations appreciably alter property fields in the very near (influence) region of nuclei and droplets? (water vapor, airflow, proticulates, temperature)	Guide to realistic physical model of growth processes.		1
Importance and variations in importance of (1) fog initiation vs developed for process (2) property distributions in fog	Guide to alternate ways to influence fog by nucleation processes. Guide to filed assessment of modification efforts.		1
Turbulence modification of coalescence and droplet populations.			1
Identification of critical mechanisms, conditions, times, and locations in fog or prefog air which are such that potential control with greatly reduced energy expenditures is indicated.	Possible great enhancement of nucleation using presently known materials.		2
What contributions to aerosol transport do turbulence and angular wind shear make in realistic stable stratifications for fogs.	Improved prediction of required seeding rates and clearing trajectories.		1
Variations in space and time in the turbulence and wind shear in fog predictable in real test cases.	Potentially great improvement in value of current seeding technology.		1
How is fog air flow and turbulence inadvertently modified by the delivery system, e.g. air craft, blower, plume generator.	Improved Technology application and effect assessment.		3
3-d velocity fields vs time for eddies (to aid in estimating coalescence enhancement).	Generally curvature acceleration is unmeasured and thus possible coalescence enhancement is not necessarily estimated well.		2

employed in conjunction with specific limited field observations to achieve sufficiently accurate information about important fog processes.

Wind tunnel tests can provide data on turbulent transport of momentum, heat and aerosol over solid or water surfaces (e.g., Arya, 1965; Chaudhry and Meroney, 1973). Also, instruments for measuring turbulence in a water droplet environment can be developed and tested using wind tunnels. Mapping of velocity and other property fields in individual eddies may be most readily done in a wind tunnel.

Since turbulent flows are likely to provide transient conditions around droplets the study of growth in nonsteady and nonequilibrium conditions must be considered. Two methods in chambers can be utilized. One is the effect on a droplet population where the details of the processes may not be observed but statistical significance can be high (Telford, personal communication, 1974). The other is the isolated study of single droplets in a transient field or nonequilibrium state where the process may more directly be observed. Statistical significance, if it is to be achieved at all in the latter case, must come from very precise control of variables rather than from a large number of studies.

Improved numerical solution of flow around droplets including turbulence effects is one useful approach to that problem (Lee, 1974). Numerical models of fog airflow, especially for stable stratification, are fairly efficient ways of understanding the possible importance of mechanisms and variations in conditions.

None of the methods of study are self sufficient. Wind tunnel data must be tied to real fog airflow and eddy transports because of possible simulation (scaling) problems. Numerical models of turbulent flow require heavy parameterization for mathematical closure of the finite difference equations. The parameterization cannot always be derived from field observations for reasons outlined in paragraph 1. Thus a set of closely interrelated studies by different methods is required.

3.7 What Can Be Learned about Fog Turbulence By Performing Wind Tunnel and Numerical Simulations

Numerical and wind tunnel simulations of fog provide opportunities to control the relevant parameters and to perform rather complete studies at minimal costs. The numerical simulation provides the flexibility required to incorporate many parameters and to vary them, while wind tunnel simulation provides physical reality which, using current computer capability and economics, can only be achieved for turbulence by parameterization methods.

Two papers have been selected as representing the results of the main classes of mathematical approach to the incorporation of turbulence into fog processes. Rodhe (1962) represented cooling by turbulent mixing in terms of the ratio of the vertical transport of heat to the vertical transport of the water vapor. The ratio was kept constant for a given fog. Rodhe did not explicitly incorporate flow, wind shear or coefficients of eddy exchange into the model. He did consider the

relative importance of radiation and turbulence transport of heat, concluding that the weak turbulence in most fogs was dominant over strong radiation effects. Rodhe also concluded that without some turbulence fog could not occur.

Numerical simulation of airflow, thermodynamics, radiation, microphysics and turbulence in a fog model is represented by the work of Pepper and Lee (1974). Their model is a two-dimensional, finite difference approximate solution to simplified primitive equations. Turbulent transports are expressed in terms of the product of eddy exchange coefficients and gradients of the magnitude of the transported properties. Closure of the system of equations depends upon representing the exchange coefficients by functions of the kinetic energy of turbulence and gradients of the mean properties being transported. For example, the eddy transport, T_χ, of a property χ in the vertical direction is by vertical velocity fluctuations, w', as follows:

$$T_\chi = \rho \, \overline{w' \, \chi'} \, .$$

(3.6)

This is parameterized (3.6) by Pepper and Lee using observational data in three steps.

$$1. \quad \rho \, \overline{w'\chi'} \equiv K_\chi \, \frac{\partial \chi}{\partial z} \, .$$

(3.7)

$$2. \quad K_\chi = \frac{K_m}{\sigma_\chi} \, ,$$

(3.8)

where K_m is the eddy exchange coefficient for momentum and σ_χ is an equivalent turbulent Prandtl number for the property χ. For heat, conservative properties and kinetic energy of turbulence the authors use

$$\delta_h \, K_h = \delta_c \, K_c = \sigma_Q \, K_Q = K_m \, ,$$

(3.9)

where the σ's $\div$ 0.7 (from atmospheric and wind tunnel data). The third part of the parameterization uses data for neutral stability turbulent flows to represent K_m in terms of kinetic energy of turbulence, Q.

$$3. \quad K_m = \frac{0.3 \, \rho Q}{\partial V/\partial z} \, ,$$

(3.10)

where ρ is the density of air and V is the wind speed. The result of these three steps is that the vertical eddy transport of χ is parameterized according to the relation

$$\overline{w'\chi'} = \frac{0.3Q}{\sigma_\chi} \, \frac{\frac{\partial \chi}{\partial z}}{\frac{\partial v}{\partial z}} \, .$$

(3.11)

It is instructive to discuss the validity of this parameterization, which is far more complete than many which are used for $\overline{w'\chi'}$. Its

estimation from measurements of w(t) and χ(t) requires

1. Accurate measurement with adequate and identical resolution in time of both w(t) and χ(t) and,

2. Proper incorporation of the theory of random time series in both the measurement and computational stages.

This may not always be done or be possible.

The value of σ_χ, a turbulent Prandtl or Schmidt-type number, is not well known for fog conditions for all properties of interest. It is also clear that both χ(z) and V(z) must be known in the region where the $\overline{w'\chi'}$ process is of interest if verification of the model parameters and results is desired. Finally, and perhaps more seriously, 0.3 Q (on the right side) is derived from several aspects of turbulent transport for neutral static stability flow but is often applied to hydrostatically stable fog where, likely, it is in considerable error. Apparently (Lee, 1974) the only reliable data for turbulence transports and other turbulence properties in stable conditions are from a few wind tunnel experiments (Chaudhry and Meroney, 1973 and Arya, 1965). Turbulence having a given kinetic energy,

$$Q \equiv \rho(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \quad , \tag{3.12}$$

may transport properties by varying rates depending upon differences in mechanism for generation of the w' and χ' components of $\overline{w'\chi'}$ as well as for v', u'. The coefficient 0.3 and σ's in Eq. 3.11 both represent specific values of cross correlation coefficient

$$R_{u'w'} = \frac{\overline{u'w'}}{(\overline{u'^2}\ \overline{w'^2})^{\frac{1}{2}}} \propto \frac{\overline{u'w'}}{Q} \quad . \tag{3.13}$$

These values may change significantly for stable stratification and are not adequately known for fog or in the wind tunnel.

3.8 Reasons for Careful Design and Interpretation of Simulations and Field Measurements

Several mechanisms may concurrently generate turbulence and several mechanisms may be involved in determining the current mean value property distribution $\overline{\chi}(z)$. Either a steady state distribution or a changing distribution $\overline{\chi}(z,t)$ may exist. If measurement of direct processes such as $\overline{w'\chi'}$ or radiation energy are not made then they must be inferred from other measurements. Some examples of unknowns which invalidate such inferences are suggested in the following analysis.

Consider a vertical profile of property χ (as shown in Fig. 3-2). If the region z = 0 to z_t were to become completely mixed and there were no sources and sinks the profile would become $\chi = \chi_m$. This is independent of the distribution of K_χ since only the final state is considered. Next suppose that the top half of the χ profile is

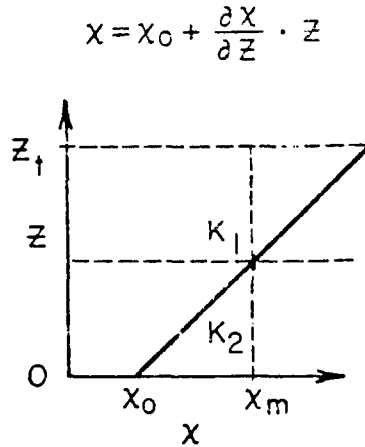$$\chi = \chi_0 + \frac{\partial \chi}{\partial z} \cdot z$$

Fig. 3-2. A simple vertical profile of water vapor mixing ratio and water vapor eddy mixing coefficient.

maintained by χ advection and turbulent transport (K_{χ_1}) while the the bottom half is maintained by a source of χ at $z = 0.5z_t$ and turbulent transport (K_{χ_2}). How the profile got to its present shape is not considered. Since the profile does not change, the source and sink must have equal strength. Since K_1 and K_2 (constant $\partial \chi / \partial z$) are not equal, the sink must be at the interface between K_1 and K_2 regions. If one were not aware of the existence of the sink, then a fictitious K_2 would be required to satisfy the steady state profile. A fictitious sink at $z = z_t$ would also be required. Similarly if the advection were not observed then it or some other functional source - sink in region z would have to be postulated. If $\overline{w'\chi'}$ were measured in each layer then the transport rate estimate would not depend upon other measurements. The location of source and sink would then be determined by the additional measurement of the $\overline{w'\chi'}$ profile since the source strength is

$$s(z) = \frac{\partial \overline{w'\chi'}}{\partial z} (z) . \qquad (3.14)$$

If the $\overline{\chi}$ profile is also measured the turbulent mixing coefficient can be computed directly using

$$\rho \, \overline{w'\chi'} = K_\chi \frac{\partial \overline{\chi}}{\partial z} . \qquad (3.15)$$

If it is required to parameterize $\overline{w'\chi'}$ or K_χ using other mean and turbulence flow variables it may be necessary to take into account the contributions of different mechanisms of turbulence. The reason is indicated by the following brief analysis.

Consider a parcel of air at the surface of the earth whose buoyancy is due to water vapor excess only. The parcel may then rise against either positive or negative vertical gradients of water vapor mixing ratio, χ_V, as long as the ambient air density is less than that of the parcel. Figure 3-3 shows a hypothetical example of transport against the gradient. This dilemma is partly due to a definition of the gradient of $\overline{\chi_V}$. It may also be partly due to the fact that mxing does not occur for small enough scale or the average is not computed over long enough times.
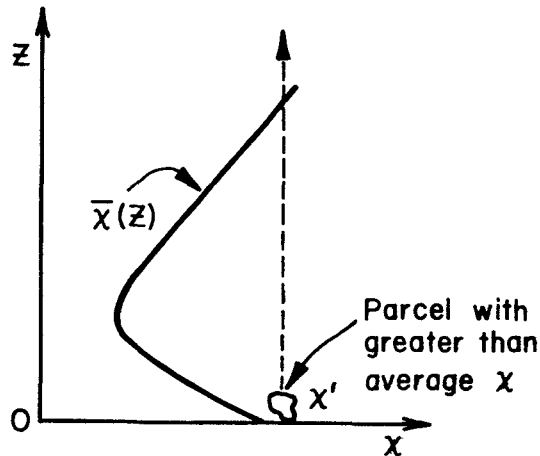

Fig. 3-3. An example of eddy transport against the mean gradient.

A second consideration of importance is that turbulent kinetic energy may be due to several mechanisms which transport property χ differently.

Then

$$\overline{w'\chi'} = (K_1 Q_1 + K_2 Q_2) \frac{\partial \overline{\chi}}{\partial z} \qquad (3.16)$$

where Q_1 is the kinetic energy associated with process 1. If there is a constant partition of turbulent kinetic energy between the two processes,

$$Q_1 = K_3 Q_2 \qquad \text{then the transport becomes} \qquad (3.17)$$

$$\overline{w'\chi'} = (K_1 + \frac{K_2}{K_3}) Q_1 \frac{\partial \overline{\chi}}{\partial z} \qquad \text{or}$$

$$(3.18)$$

$$\overline{w'\chi'} = (\frac{K_3 K_1 + K_2}{K_3 + 1}) Q \frac{\partial \overline{\chi}}{\partial z'} \quad .$$

It is necessary to know whether relation (3-17) is general with a constant K_3 and whether $K_1Q_1 \sim K_2Q_2$ before the correctness of the parameterization can be assessed properly.

Turbulence mechanisms may be determined by at least the following processes:

1. Rough-surface airflow.

2. Surface heating.

3. Surface evaporation of water.

4. Latent heat heating or cooling.

5. Differential advection.

6. Radiation.

7. Vertical gradient of eddy transfer of buoyancy.

The multiplicity of processes and mechanisms suggested by the examples of this section indicate a great need to carefully design new research.

3.9 Needed Small-Scale Field Measurements of the Turbulence Processes of Fog

The purpose of field measurements is to provide real-world baseline data by which to design models of fog and to test and adjust more detailed and controlled wind tunnel and mathematical models. It has been indicated in previous sections that numerical models must receive input from observations since the inclusion of all turbulence effects on all important scales cannot be done analytically or with current computer capability. Wind tunnel observations are the best economically and statistically if the problem is one of a turbulent boundary layer with a hydrostatic stability condition. There is no reasonable expectation of studying realistic atmospheric fluctuations of water vapor or droplets or fog radiation or mixing saturation in the wind tunnel. There are also reasons to wish to compare turbulence properties in the tunnel against important turbulence properties in fogs so that the wind tunnel data may be correctly applied to mathematical models of fog. Study of details of turbulence which may affect coalescence require a specially modified or operated wind tunnel. Table 3-3 contains a list of atmospheric fog measurements which are important to make and a brief notation of the importance of each measurement. A tentative priority of achievement is indicated in column 3. Property measurements are labeled with Arabic numerals. Instrument platform types and measurement methods are identified by upper case English letters.

TABLE 3-3

Small Scale Field Measurements Which are Needed

	Measurement	Importance	Priority
1.	Turbulence kinetic energy, $\overline{u'^2 + v'^2 + w'^2}$	1,3,4,5,6. Check wind tunnel data. Provide basis for parameterizing $\overline{w'u'}$ and for calculating eddy transport coefficient, K_m Check mathematical model.	1. 1
2.	Turbulence transport fo momentum, $\overline{w'u'}$		2. 1
3.	Turbulence transport of liquid water $\overline{w'\chi_i}$, $\overline{w'n'}$		3. 1
4.	Spectra of the above cross- and auto-correlations and component fluctuations, e.g. $\overline{\chi_e'^2}$, $\overline{n'^2}$	3,5,6,7. Provide basis for paramaterizing eddy transports of liquid water, droplet size distributions, heat, aerosols, water vapor. Comparison of K's for different properties. Check mathematical model.	4. 1
5.	Vertical profiles of mean values of properties in above correlations $\overline{U}(z), \overline{V}(z), \overline{\chi}(z)$ at the corresponding places and tiems of the correlation measurements.	6 Method of estimating transport of heat and water vapor if 7 is not feasible.	5. 1
6.	Turbulence and mean properties of eddy mixed gas or aerosol tracer readily observable in fog.	3,6 Determination of the relative importance of eddies and fall velecities in the transport of droplets.	6. 2
7.	Mean and fluctuating temperature and water vapor in droplet environment	A. Least expensive way to collect variety of correlated data at one or more heights.	7. 2
A.	Point or vertical line, e.g. tower or balloon.	B. More complete sampling of fog spatial variations. Trading space for time can provide more rapid acquisition of statistically stationary time series with less trend problem.	A. 1
B.	Set of horizontal-line, e.g. aircraft.		B. 2
C.	3-d field of measurements of some variables using remote sensing, e.g. acoustic methods.	C. Still more complete spatial sampling, of an intermediate size volume over very short periods of time to eliminate some trend problems in relating variables. Mean and fluctuating air flow in 3-d. Some potential for droplet and liquid water content and temperature structure both mean & eddy.	C. 1

3.10 Mean Airflow: Wind

The variability of the wind can determine the practical success of a technically successful method of fog control simply by moving the treated fog in the wrong direction or at the wrong speed. Thus very costly methods of control must be used to assure the desired effect. In Appendix A it is suggested that unless hygroscopic nucleation research or technology can result in 10 to 100 times less cost in application without requiring treatment much further upstream from the target area, very probably it will not help solve the problem. A similar remark applies to understanding and using turbulence effects in fog. The difference is that turbulence effects in fog are significant but less known and seem to offer more promise of distinct advances in understanding. Better numerical prediction of turbulence and understanding aerosol dispersion and actual microphysical process variations may make current hydroscopic nucleants much more effective. Nevertheless the wind problem remains a serious one for which some hope of improvement is held.

The winds in fog are often light and variable although fog winds up to 40 knots have been reported. Such wind fields are subject to a variety of local effects and variations are presently unpredictable. Several efforts to measure wind and other fog related properties adequately with a mesonetwork have not been successful.

This report does not contain a review and analysis of the local and mesoscale wind prediction problem. It is suggested, however, that a thorough study of the problem will have to be made for a specific site for which the following conditions exist.

1. Winds in fog are not adequately predictable.

2. Terrain, heat, pressure, turbulence and radiation conditions are simple enough to permit unambiguous analysis of probably weak but important influences on airflow.

3. An adequate set of observation sites be set up or added to until the wind variations observed can be explained. Remote (acoustic) methods may be required in part.

4. If a need for fog control at the site exists it is with a priority such that adequate time can be taken to perform the required study and undisturbed by fog control procedures.

The tests of understanding initially should be threefold.

1. A field-of-flow-measurement which permits knowledge of the airflow in adequate space and time resolution. Trajectories of mean flow in the network should be a minimum of 15 minutes long, i.e., 2-6 miles long.

2. Limited tracer studies which can verify mean trajectories vs. height and, secondarily, estimate dilution due to turbulence and wind variations with height.

3. Development of mathematical prediction of airflow.

    a. The preliminary model should be run only when data analysis shows that the wind field is adequately observed.

    b. Immediate attempts must be made to determine the model errors which cause discrepancies and to determine if the proper observations can be made to permit correct modeling.

    c. The instrumentation required must be added if the measurement is possible. Otherwise mathematical models which indirectly determine the required parameter must be developed. If this is not possible, a climatological scheme must be used for the otherwise unpredictable components of the flow.

The program suggested in this section may seem too elaborate. However useful prediction of winds in fog is a goal that presently appears to have a fairly high priority. Success in prediction will have applications well beyond the fog problem. Lesser efforts have apparently failed.

3.11 Plume Mixing and Rise

A fog may be artificially or naturally modified by plumes of low humidity air and of hygroscopic nuclei. The plumes may be horizontal, ascending or descending, buoyant or not buoyant. They may be generated in different ways resulting in different initial mean and turbulence velocity fields. Knowledge of the mixing rates of the plume with its environment are essential. The mixing may be divided into three possible spatial zones: (a) at the source of heat or nuclei, (b) the plume just beyond the initial zone and (c) the "far-field" plume. While there is a great deal of experience in plume dispersion some significant lack of understanding exists. No attempt has been made to survey all the potential problem areas as a part of the present review.

For heat plumes in a crosswind vertical suppression by wind of modest speeds is a problem (Rogers, Mack and Pilié, 1972). Efficient methods of controlling vertical penetration and mixing for a wider range of wind conditions are required.

The author is not aware of studies of the effects of the initial turbulence field for aerosol released from aircraft nor of the influence of aircraft-induced flow and turbulence upon fog directly.

3.12 Recommendations for Research in Airflow, Turbulence and Fog Property Fluctuations

The greatest restrictions on effective application of nucleation to fog modification due to airflow, turbulence and fluctuations of properties would seem to be related to the following.

1. Prediction of mixing and airflow trajectories in fog.

2. Turbulence mechanisms of coalescence in fog and near the dispersing system for both nucleant and small fog droplets.

3. Nonaverage properties and process intensities in individual parcels of fog air.

4. Uncertainties in predictive fog model, numerical or derived from field measurements, used as a reference for evaluating seeding either in the field or numerically modeled.

It is recommended that highest priority be given to the following studies.

1. Wind tunnel simulation of a range of stably stratified boundary layers and measurement of mean profiles, fluctuation intensity and cross correlations for eddy vertical transport of momentum and heat. Parameterization of the eddy flux in terms of quantities other than the cross correlation should be derived.

2. Observation and numerical simulation of the coalescence of larger than one micrometer diameter particles in Kolmogorov microscale (dissipation zone) shears both having the detailed structure as observed in fog and as readily generated by mechanical means.

3. Selected measurements in real fog by which to better relate results of nonfield studies 1 and 2 to real fog properties. This implies (a) concurrent and cospatial measurement of mean property profiles and turbulent and fluctuating properties and (b) rapidly repeated measures of velocity and turbulence structure, at least, at a number of different but related positions in the fog.

It is recommended that doppler acoustic sounding be utilized for making the rapidly repeated measures over a few hundred meters range, especially vertically. It is recommended that a balloon system or tower be used for in situ measurement of parameters. Finally an 0.89 cm doppler radar should be used to describe the mean and perhaps turbulent field over mesoscale range of fog.

3.13 References

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Chapter 4

INSTRUMENTATION FOR MEASUREMENT OF WINDS, TURBULENCE AND
FLUCTUATION OF FOG PROPERTIES

4.1 Introduction

A discussion of instrumentation is presented because certain
required measurements are difficult to make. Some of the important
types of inadequacies are as follows:

1. Resolution in space and time.

2. Instrument output is a function of more than one property
    which fluctuate and are not independently known.

3. Space and time span of observations.

4. Individual parcels cannot be followed by the sensor.

5. Time lag between measurements at different spatial positions.

6. Imprecision in three dimensional navigation and orientation
    in fog (near the surface of the earth).

7. Sample size, sampling rate and total measured population.

8. Cost-logistics.

9. Disturbing the quantity being measured.

Reviews of modern instrumentation for atmospheric science have been made
within the last few years. The significant advances indicated by the
reviews and other more specific analyses generally have been in the
use of digital computer and microelectronics techniques, remote sensing
by wave methods and development of a few specific sensing principles.

Precision determination in real time of platform position and
orientation has been a significant new step in atmospheric measure-
ment. On the other hand upgraded and better-understood classical methods
of sensing still are the main bases for needed and high quality data.
A detailed review and analysis of all relevant instrumentation is not
written here. Rather, some of the major problems will be indicated
along with the cause of the problem and suggested directions for
research and development to solve the instrumentation aspects of the
problems. The details of solution may sometimes depend upon the field
of measurement, e.g., mesoscale, point-atmospheric or laboratory. No
subclassification of instruments along these lines will be made system-
atically in this chapter on the assumption that the specific conditions
of use will make obvious the correct selection of instrument and method.
A set of general references on instrumentation is included in the
Reference section.

4.2 Methods of Reaching the Desired Points of Measurement: Platforms
and Remote Sensing

4.2.1 Systems Useful in the Study of Fog

In addition to solving the inadequacies listed in section 4.1 it
is necessary to be able to properly place the instruments at the points
where measurements are desired. Fog forces restrictions upon methods
of placement of sensors for the following reasons.

    a. Reduced visibility: mobile platform. Navigation is more
        difficult, costly and hazardous.

    b. Low and variable wind speeds. Measurement accuracy closer
        to limits of sensitivity of sensors means that instruments
        must be more carefully placed with respect to platforms and
        auxiliary equipment.

    c. Liquid water content may be altered or may interfere with
        "normal" operation of sensors.

Four methods of reaching the site of observation must be considered in
evaluating instrumentation development requirements. They are discussed
briefly in the remainder of this section.

Towers are readily accessible extensions into the boundary layer
which are quite useful. They are limiting because they are fixed and
generally not tall enough. They are expensive to instrument and
maintain for profile measurements. The most effective tower carries
instruments on an elevator on its side. Mobility, reach and the number
of measurement sites are often less than desired when towers must be used.

Airplanes provide rapid mobility in three dimensions. Precise
orientation, navigation and vertical positioning are difficult but
possible. Existing and somewhat improved inertial platforms, radar
altimeters, pressure altimeters and radio navigation can be used together
to achieve the goals in fog. This total system is both initially costly
and costly to maintain. Data acquisition from aircraft and subsequent
analysis and interpretation require special statistical and physical
consideration of the variations which may occur in the atmosphere.

Balloon and hybrid-balloon platforms appear to be very useful for
fog studies. They may be tethered or mobile in three dimensions by
several methods of movement. Their speed of movement relative to air
and ground can be slow. Instruments may be moved up and down below
them for profiling. Their cost can be moderate so that multiple instal-
lations are feasible. As with airplanes some attention must be given
to motion and orientation of the platform. Tethered balloons have
generally provided acceptable results for measurement of most atmo-
spheric properties including intensity of turbulence but not for direct
measurement of eddy flux. A suitable method of positioning, stabilizing
or measuring the motion of eddy flux sensors must be developed.

Remote sensing techniques (passive and active wave propagation methods) offer the best opportunities to measure at numerous points along lines, surfaces and in volumes rapidly and repeatedly. These systems may be fixed or mobile on the earth's surface or airborne. If the doppler shift aspect of the method is used it requires corrections if the platform is moving appreciably. In addition to measuring some of the properties also measured by more classical methods, some wave methods provide measures of other potentially useful properties as will be indicated in a later section. Most of the systems are expensive, but in terms of cost per useful data point they are probably less expensive than other systems. Further they generally do not modify significantly properties in the region being measured. Finally, the measurement of large fields of variation may not be otherwise possible. Cost, mobility and power requirements are problems which could be reduced in magnitude. Certain uses of these methods will be practical only after further study and development.

4.2.2 Laboratory Application of Remote Sensing

Wind tunnel and chamber measurements are generally made using mechanical probes to place a sensor or to withdraw samples. These methods sometimes interfere significantly with the process being studied. Remote sensing, especially by laser devices, involving the use of doppler shift and scattering from inhomogeneities would be of special value in this regard. Some study and development is required to reduce costs, improve the measurements now performed and facilitate some potentially useful methods.

4.2.3 Recommended Development of Platforms and Remote Systems

It is recommended that state of the art technology be focused on development of a small-balloon platform which may be tethered or remotely piloted in fog with three-dimensional position and orientation capability. Incorporation of a simple, lightweight three axis platform and wave propagation positioning and orientation measuring techniques designed for meso and smaller-scale range from 2 m to 1000 m off the ground would have great value extending to mesoscale studies generally. The maximum air speed of the balloon would probably need to be about 20-30 ms^{-1}.

Precise high resolution three dimensional navigation and orientation equipment, digital computer and data storage, telemetry and transponder systems should be made accessible from the state of the art devices so that smaller powered airplanes can be used as sophisticated research vehicles.

Two methods of remote sensing are especially important to fog studies. They are the pulsed acoustic and the 0.89 cm electromagnetic doppler sounders and their coherent multiwavelength counterparts. They can readily measure velocity of fog parcels as well as fluctuations of temperature (acoustic) or velocity (acoustic and electromagnetic) and hydrometeor properties (acoustic and electromagnetic). Some theoretical work must be completed as well as must some research with the developed

instruments in order to adequately understand the hydrometeor data, especially. These remote systems will be discussed more fully in subsequent sections of the present chapter.

4.3 Mean Velocity, Trajectory and Turbulence

Special measurement problems require a separation of the topic of airflow and transport properties into the following properties:

a. Velocity, both mean and turbulent.

b. Trajectory and spread of particulate clouds.

c. Turbulent transport of properties (eddy cross correlations).

4.3.1 Velocity

Table 4-1 contains a list of the most useful and most promising methods in column one. Columns two and three describe their application and limits of application respectively. Suggested additional development of each instrument, method of use and interpretation is indicated in column four.

There is a great need to know the wind, vertical motion and turbulence nearly instantaneously and repeatedly at short intervals from the top to the bottom of a fog and for horizontal extents of from zero to a few kilometers. This can only be achieved using wave sounding methods. For fog the most promising instruments are "acdar" (acoustic ranging and detection) and 0.89 cm radar (which sees fog droplets) in the doppler modes. To the author's knowledge only one doppler 0.89 cm radar is currently in use in the world (by Japan, in fixed vertically-pointing mode). The 0.89 cm radar could have a very narrow beam and could track clear and fog patches for useful trajectory data. The dopler information would provide information needed for understanding the trajectories in terms of local boundary and meteorological conditions. In addition to aiding in improvement of airflow and mixing modeling, real time decisions could be made to improve modification using current hygroscopic methods. Longer wavelength radars require excessive power and even then do not provide adequate energy scatter from small fog droplets. The acdar is a very low cost device by radar standards. Sound scatters from velocity and temperature fluctuation regions as well as from very sharp gradients of these quantities and from hydrometeors. The amount of scatter is up to 1000 times that for radar energy. Further the techniques for acoustic signal handling are essentially low frequency ones thus reducing the cost and complication of "acdar" as opposed to radar. A few examples of the properties and use of "acdar" are provided in Figs. 4-1 through 4-7. Very few universities or other laboratories are using doppler "acdar"; however, the Wave Propagation Laboratory of NOAA-Boulder is continuing use and development of doppler "acdar." Special antenna baffling techniques have controlled city noise and noise due to winds for $V < 10$ ms^{-1} at the antenna. To some extent light precipitation and portable power generator noise can be excluded from the signal.

TABLE 4-1

Velocity Instruments: Applications Needed Development

Measurement Method	Fog Application	Space, frequency wavelength resolution	Suggested R & D on instruments or physics
drag, thrust, strain	B.L. velocity, fluct'n cross correlation	~ 10^3 cm^3 "point" Hz	none. well understood in range of applicability
rotating sensor of speed	B.L. velocity, fluct'n, cross correlation	~ 10^4 cm^3 "point" λ > 6 - 8 m	none. although turbulence errors in speed and direction
pitot tubes and vanes (on aircraft)	PBL velocity, fluct/n, cross correlation	~ 10^4 cm^3 λ > 4 m	none. although faster responding vanes could be used
hotwire and hotfilm (on any platform)	PBL velocity, turb., cross correlation, droplet, temp.	10^{-2} cm^3 "point" 10^{-1} to 10^5 Hz	improve understanding of response to droplets, temp. and nonperpendicular flow
ultrasonic speed of sound	PBL velocity, turb., cross correl'n, vapor, droplet, temp.	10^{-3} cm^3 "point" 10^{-4} to 10^2 Hz	improve understanding of response to droplets and operation in fog.
sonic "acdar" scatter and doppler shift	PBL velocity, turb., T & Vel. Fluct., hydrometeor	~ 10^3 cm^3 "point" 35 - 400 m range ? - 0.2 Hz ?	multifreq. response to droplet distrib'n. Silent mobile electrical power.
Tracer detection (a) radioactive (eg Kr 85)	{ PBL local to 5 km and even to 100 km from source.	(a) 10 cm - 5 km funct. of concentration	(a) none.
(b) scintillating (eg ZnS) (d)		(b) 10 cm - 5 km	(b) increase signal to noise higher volume rate of sampling, real time read-out and recording
(c) chemical		(c) ?	(c) none. although mod. for acft to decrease bulk and fire hazard would be useful

The doppler-derived data in Figs. 4-1 through 4-5 are obviously of the type needed for fog studies. Figure 4-5(a) contains an example of nondoppler measurement of thermal structure. Figure 4-5(b) shows the backscattered intensity distribution for the same section of plume.

Figure 4-6 shows that sound waves are much less attenuated in totally dry or nearly saturated air. Thus the range of an acoustic sounder is markedly increased in saturated air. Secondly, a multi-frequency scan can provide data for determining relative humidity since $\frac{\partial a}{\partial f}$ = g (a function of rel. humidity) where a is absorption coefficient and f is the acoustic frequency. Similarly the droplet scatter is a function of diameter and wavelength so that droplet spectra are in principle derivable from "acdar" signal echoes.

Figure 4-7 contains a set of curves of scattering cross section as a function of scattering angle for each of atmospheric water droplets, velocity fluctuations and temperature fluctuations. One important point is that the scattering due to droplets can be ignored or looked at alone by proper choice of scattering angle. The practical utilization of these latter phenomena require further research and development.

The sensitivity of one instrument to several parameters is an old measurement problem which is found in many of the new instruments. However, opportunities for better cross correlation measurements come with the difficulties. This is potentially the case for most wave propagation methods. It is also true of the hotwire and hotfilm sensors discussed below.

The need for a fast-response velocity sensor for fog research is threefold. First, it is becoming apparent that very small (microscale) eddies cause small fog droplets to coalesce. Further, fog variations occur on small scales. Finally, aircraft are needed to get sensors directly to many regions of fog and its environment rapidly. Since the aircraft moves rapidly, fast response sensors are required to delineate the smaller scale (< 5 m) structure. Hotwire, hotfilm and lidar sensors are the most useful fast response velocity sensors. Doppler lidar is quite expensive for simultaneous multiaxis velocity measure-ment but is uniquely useful. There is no mechanical sensor to be damaged or to interfere with the measured volume of air. The hotfilm anemometer can resolve the three directional components of velocity but also responds to temperature and fog droplets. The latter effect may be very strong in fog at high speed.

In principle a three-axis split hotfilm sensor can measure temperature, velocity, droplet size and concentration simultaneously and nearly continuously over very small instantaneous volumes. If there are 100 10-micron droplets in a cubic centimeter of volume traversed by a hotfilm having a "frontal" area of 10^{-2} cm^2 then a maxi-mum of one droplet would strike the film. If the film were moving at 50 ms^{-1} a droplet impaction would occur about every 10^{-5} s. Under these circumstances the velocity signal would be obliterated unless the droplet spikes vanished in less than 10^{-6} s. Only one reported study
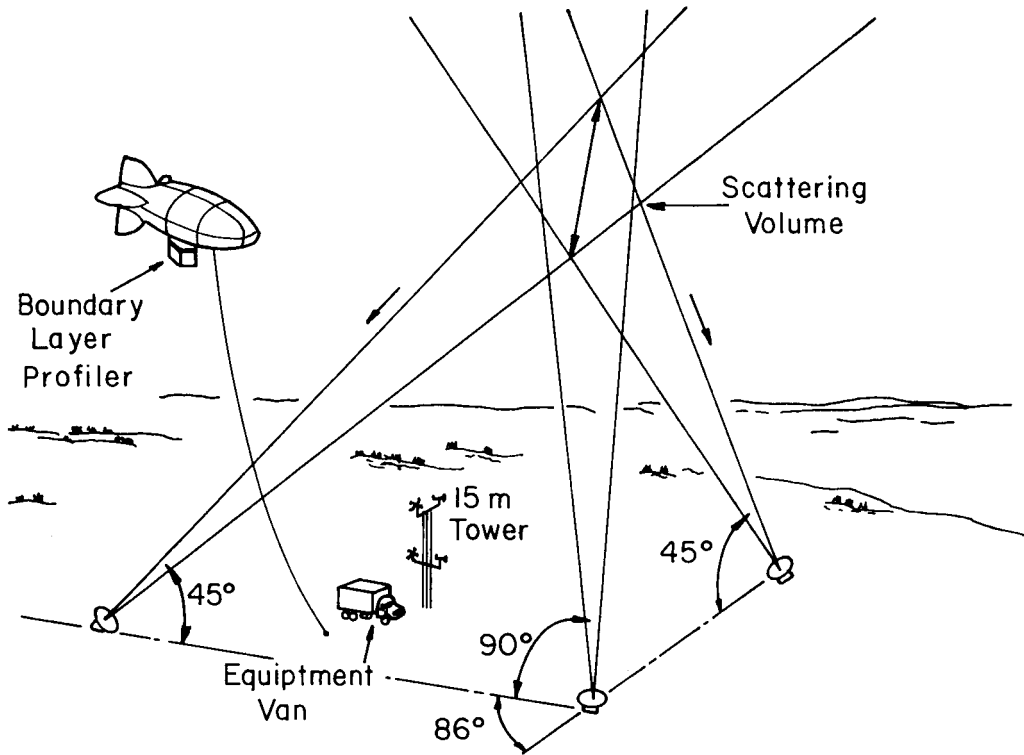
Fig. 4-1 Arrangement of three acoustic echo sounders, with supporting
equipment, used to measure the total wind vector by analyzing
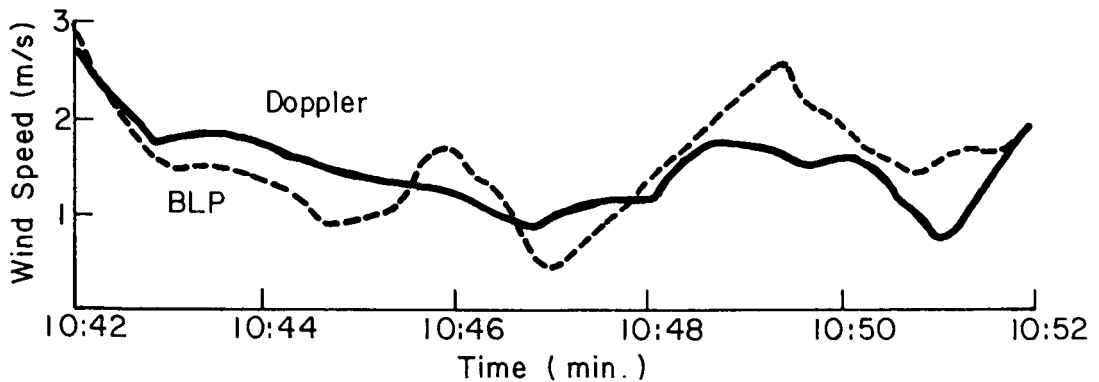the Doppler shift in back scattered sound. (After Beran and
Clifford, 1972.)

Fig. 4-2 Comparison of wind measurements by acoustic Doppler and an
anemometer on the boundary layer profiler (BLP) balloon (time
lagged to compensate for differing positions, and low pass
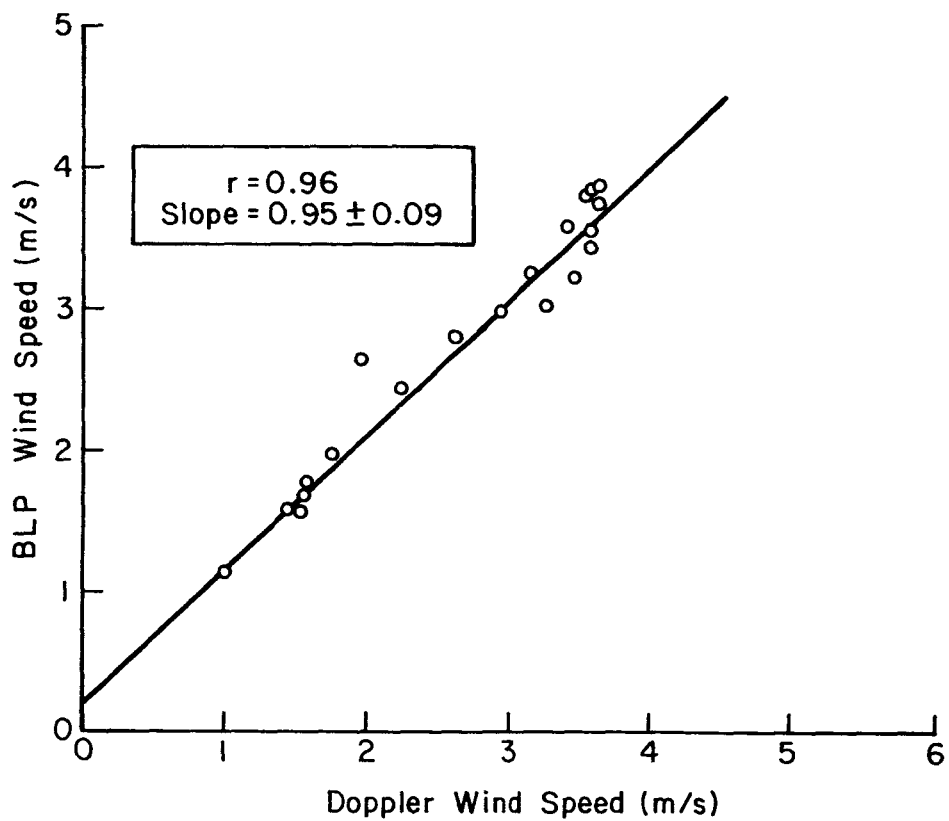filtered using a one minute time constant). (After Beran and
Clifford, 1972.)

Fig. 4-3   Scatter diagram comparing Doppler and BLP wind measurements, time lagged to compensate for differing positions, using a two minute constant and 30 minutes of data.   (After Beran and Clifford, 1972.)
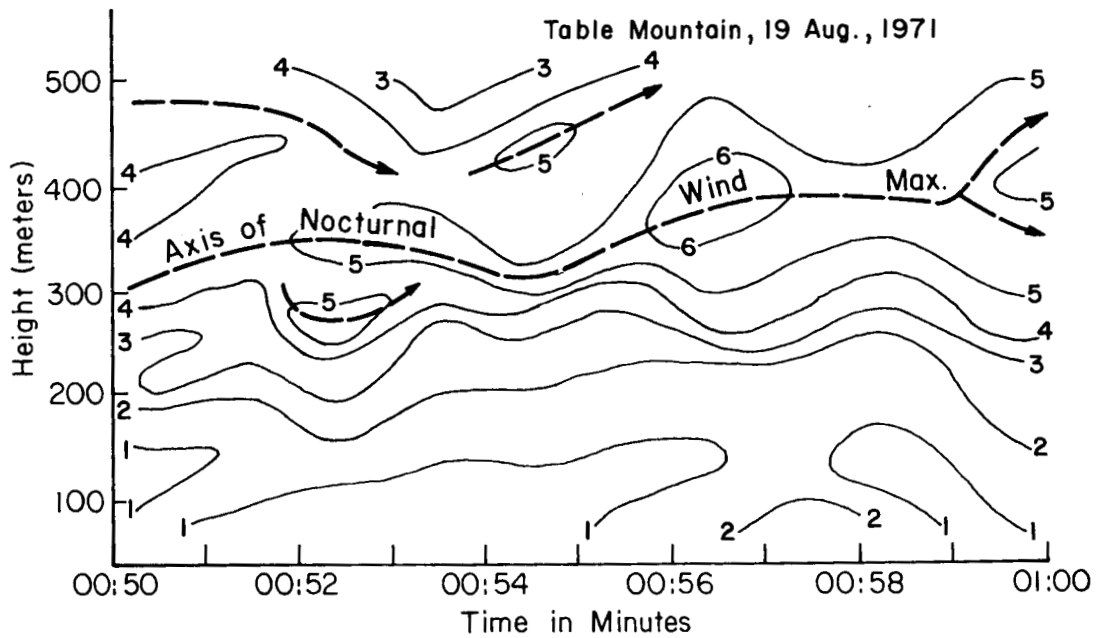
Fig. 4-4 Isotachs of the horizontal wind in ms^{-1} , measured by the
acoustic Doppler technique; an oscillating temperature
inversion extended to a height of about 250 m. (After
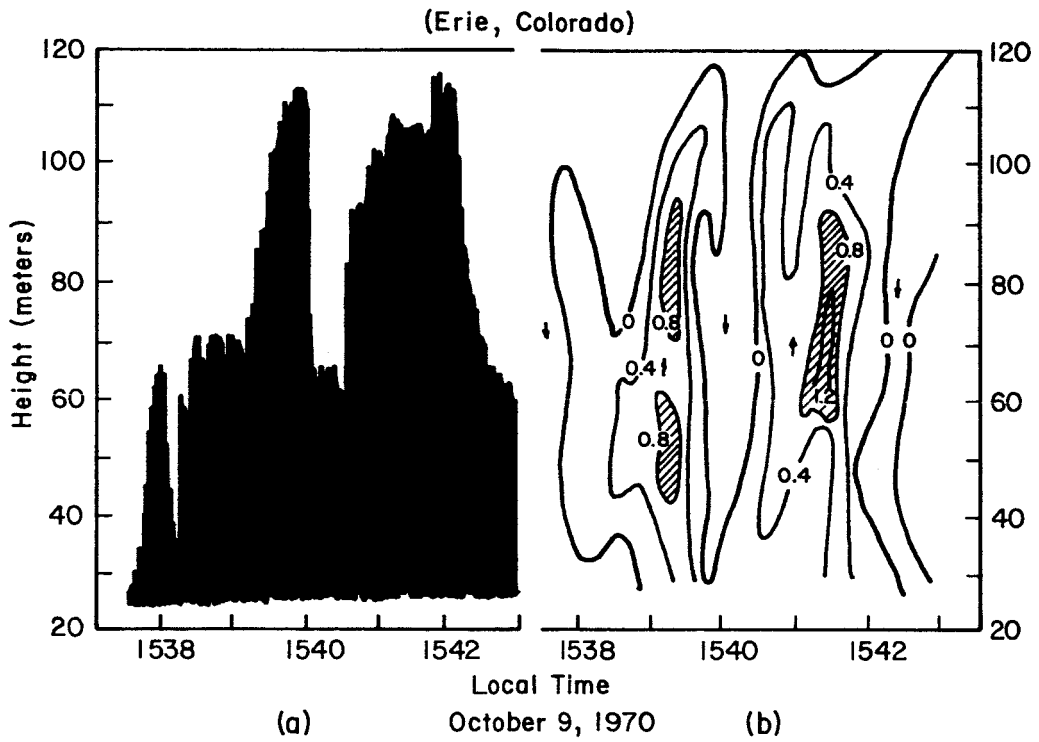Beran and Clifford, 1972.)

Fig. 4-5 (a) Facsimile record of convective plumes backscatter intensity and (b) Doppler detected wind in ms^{-1} for the same plumes as in (a). (After Beran, et al. 1971.)
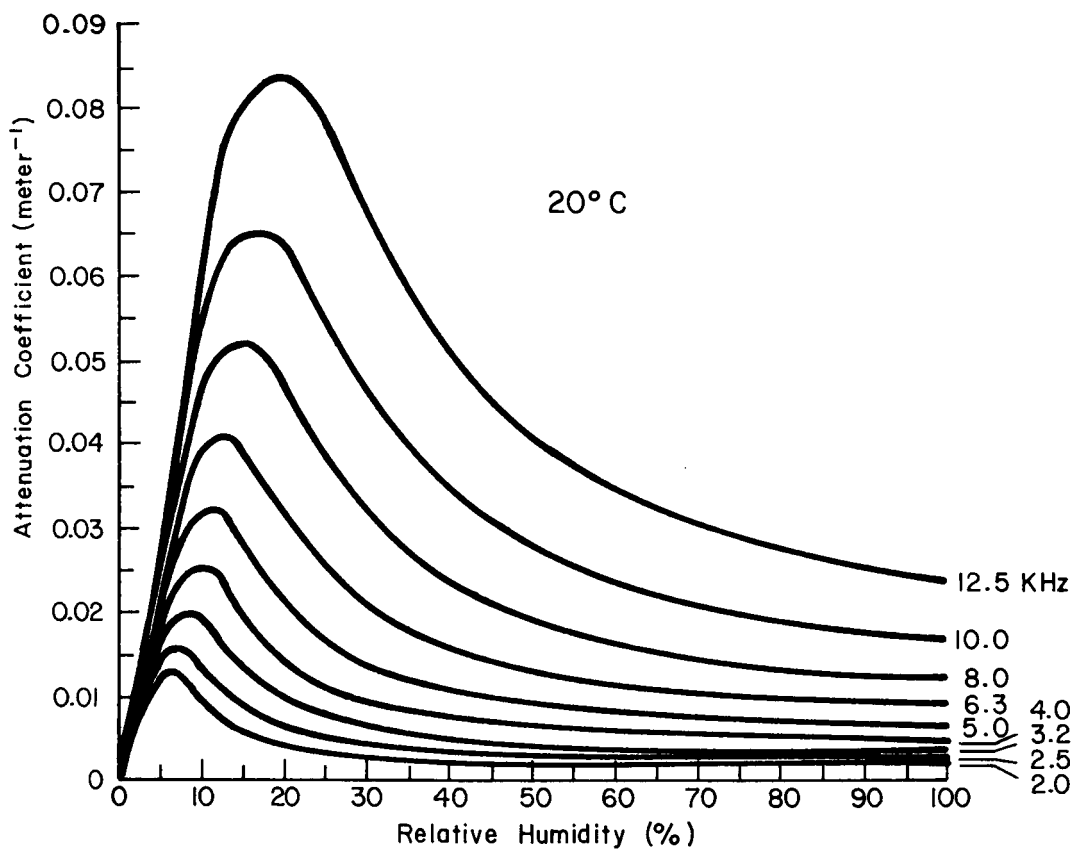
Fig. 4-6 Molecular attenuation coefficients for acoustic waves as a
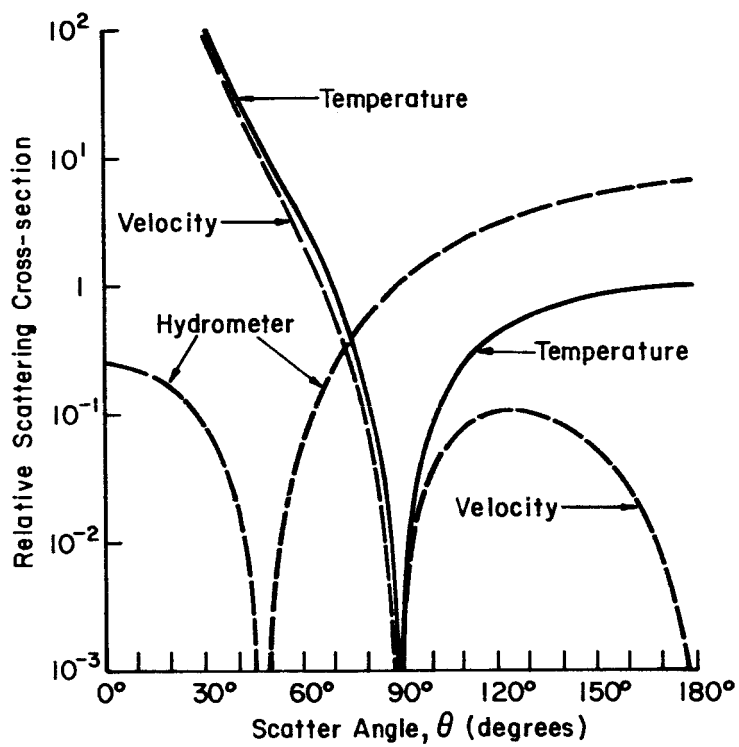function of humidity for various frequencies. (After
Little, 1969.)

Fig. 4-7   Angle dependence of acoustic scatter from hydrometeors and
a Kolmogorov spectrum of temperature and velocity fluctuations.

4.3.3 Turbulent Fluctuation of Properties

For determination of eddy transports the instruments must measure fluctuations of velocity and the property transported in the same place and time, with the same time and "space" constants, using a space and time resolution which "captures" most of the eddy transport. In low winds and for fixed instrument platforms the main problem in measurement response time is with liquid water content and droplet spectra, ignoring the problems of multiple-property interference in the measurement. For measurement from airplanes, water vapor, temperature, wind speed and direction are important factors also. Table 4-2 contains a list of required but inadequately achieved measurement capabilities for fluctuation and flux measurements. In column two are cited some reasons for the inadequacies and Column 3 contains some suggested potential solutions. It should be noted that while radiation energy R is not expected to be transported by air velocity $\vec{V}$ the fluctuation of radiation energy $\overline{R'^2}$ may be important (Kumai, 1973). The autocorrelation of fluctuation of other variables may also be important to fog by widening the intensity variation of microphysical processes.

The review of the literature made for the present analysis was not comprehensive but was intended to provide a preliminary estimate of the areas where research and development is required. In particular, some of the instruments (e.g., hotwires) may be widely used in fields other than atmospheric science and fluid mechanics. Some of the inadequacies listed may have been overcome by workers in other fields. These fields should be identified and their literature should be reviewed.

4.4 Summary Recommendations for Instruments to be Developed or Improved for Study of Airflow Turbulence and Property Fluctuation

In order to perform adequate measurements of fog airflow, turbulence and fluctuation of other properties, improvement of a number of existing instruments is required. This is also true of certain needed laboratory chamber and wind tunnel measurements. The main areas of development needed are related to passive and active wave propagation, microelectronics, navigation and orientation systems, miniaturization, turbulence sensors and balloon-platforms. The author suggests that the most needed improvements are for 0.89 cm doppler radar, multifrequency doppler "acdar" a miniature precision navigation and orientation measuring system, 2-3 axis doppler laser having 1-2 meter range and improved understanding of the response of hotfilms to fog droplets and temperature fluctuations. Water vapor measurement in a droplet environment must be made accurately with fast response times. Wave propagation methods seem to be the most promising.

It is recommended that the highest priority be given to improvement and development of multifrequency doppler "acdar", to local 2-3 dimensional velocity measurement in a droplet environment and to local absolute water vapor fluctuation measurement in a water droplet environment. The next order of priority should go to narrow beam 0.89 cm doppler radar for fog airflow observation and to temperature fluctuations in a water droplet environment.

Table 4-2. Turbulence fluctuation instrumentation: needed improvements.

Measured Property	Reasons for Inadequacy	Potential Solutions
Air Velocity	Cup overestimation of mean wind in turbulence	Use bidirectionally symmetric devices
	Momentum of liquid water	Independently measure liquid water and compute correction use method which filters out effect
	Motion of platform unmeasured	inertial platform and wave propagation methods of measuring position and orientation.
	response of instrument to several variables, T, $\vec{V}$, χ_v, χ_{drop}.	Determine component responses and possible nonlinear interaction. Perform several independent method measures of variables.
	number of "acdar" pulse returns required for statistical significance	learn limitations, study higher f and pulse rate
	spatial range covered and speed of coverage	wave propagation methods for larger volume coverage. Aircraft for small instantaneous volume, large space-time coverage
	spatial resolution (a) mechanical size (b) wave and beam dimensions.	miniaturization short wave length, narrow beam.
	Inadequate theory and calibration. Deviation from ideal characteristics, e.g., (a) yawed hotwire (b) temp. response of hotwire (c) wave scatter	research on theory and observational description of characteristics.
	Perturbation of measured quantity by (a) instrument (b) platform (c) auxiliary equipment	use wave propagation method study effect of platform and auxiliary equipment
	low sensitivity	improve signal to noise of electronics
	response time	use wave and hotwire methods and increase range of doppler shift frequencies.
	data handling including computation of property from calibration equations and cross correlations	improve and miniaturize online analog and digital transmission and computation
Dry bulb temp.	water droplet collection and evaporation	droplet wave techniques test vortex including 60 G/H₂M wave in controlled conditions. Meas. d & χd & compute correction

Table 4-2 Continued

Measured Property	Reasons for Inadequacy	Potential Solutions
Dry bulb temp.	radiation heating	study effect in fog where scatter may be strong.
	size of element, heat conducti-vity and capacity	wave techniques
	lags due to liquid water removal methods	miniaturize vortex and reverse flow devices
Water Vapor	response time response to other variables	Use wave techniques; improve Infra Red or Lyman α or 0.5 G Hz microwave.
	liquid water contamination of sensor	Understand ways of correcting for other effects on microwave refractometer.
		methods of removal of liquid water mechanically or by heat but with no known evaporation
Liquid Water	Low liquid water contents poorly understood hotwire response to spectra instability of hotwire for absolute measurement	multifrequency passive microwave ~ 10.7 G Hz Laser size & number density device for 10μ droplets Acoustic scatter of 90° scattering angle improve hotwire methods develop fast evaporation method.
Radiation which influences heating of fog	Liquid water or sensor	develop aerodynamic shield from liquid water.

4.5 References

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Chapter 5

SUMMARY OF RECOMMENDATIONS FOR RESEARCH
RELATED TO WARM FOG MODIFICATION

Chapters 2, 3 and 4 contain suggestions for needed research and instrument development in "quasi-steady state" microphysics; airflow, turbulence and fluctuation microphysics; and instrumentation for airflow, turbulence and fluctuation of properties respectively. In each chapter an estimate of priorities is presented. Based upon the suggested research needs and estimated priorities, recommendations are given corresponding to the topic of each chapter. The present chapter provides a less detailed and coordinated set of recommended research topics drawn from the preceding chapters. All items listed below are of the highest priority. Within this high priority classification, the items within each section are given in order of decreasing priority.

Microphysics

1. Experimental verification of "quasi-steady state" theories of nucleation, growth and evaporation.

2. Effects of fluctuations in environmental properties (temperature, water vapor) on microphysical processes. Is there any effect other than that which would be expected by superimposing these fluctuations on a steady-state model?

3. The effects of pollutants on a fog (inadvertent modification).

4. Study of the composition of natural CCN in various environments (marine, continental, polluted, etc.) and experimental means of measurement.

5. Study of the possibility of poisoning CCN; poisoning materials and their effects on CCN having varying compositions.

6. A search for more suitable nucleating materials; nontoxic, noncorrosive, easy to handle, reasonably efficient.

7. Development of rapid-response, precise instrumentation for the determination of saturation ratios in the vicinity of unity.

Turbulence, Airflow and Fluctuations

1. Wind tunnel, chamber, field and mathematical studies of coalescence of aerosols and droplets due to velocity shears and factors which affect coalescence efficiency.

2. Wind tunnel measurement of mean and turbulent properties of stably stratified flows for a range of applicable Richardson's Numbers. Improved parameterization of eddy transports of momentum and scalar properties is to be achieved.

3. Advancement of the use of "acdar" (acoustic "radar") to measure a variety of fog parameters.

4. Development of a compact mobile 0.89 cm narrow beam Doppler Radar for up to mesoscale range wind velocity and turbulence measurement in fog.

5. Advancement of methods of measuring 2-3 dimensional turbulent flow in thermally fluctuating air and a water-fog environment.

6. Development of instruments for accurately measuring absolute temperature fluctuations and water vapor fluctuations in a super-saturated environment. Interference of water fog droplets with the measurement should be considered.

7. At least minimal field study with the objective of tuning laboratory and mathematical simulations to real fog airflow, turbulence and fluctuation microphysics especially in order to understand mixing, dispersion and coalescence.

It is suggested that, when possible, development of instrumentation be carried far enough that reliable results may be attained routinely by technicians. Instruments should be developed for field studies also.

APPENDIX A

A.1 Relevance and Scope

The control of warm fog is relevant to problems ranging from the protection of plants from atmospheric frost or drying (by production and maintenance of fog) to the reduction of transportation costs and hazards (by diminishment and dispersal of fog). The quality of information transmission systems is sometimes degraded by the effects of fog upon wave propagation.

Many methods of modification of fog have resulted in striking success in small volumes and/or for short time intervals. However, due to our present lack of understanding of fog characteristics operational fog control is often a difficult and costly procedure. Many of the details of the problems, as well as assessment of proposed solutions and some significant new results are provided in a series of Cornell Aeronautical Laboratory NASA contractor reports dating from 1964 to 1972. The present chapter will not repeat the details of those reports. An assessment of the technology of fog modification has been published recently by Air Force Cambridge Research Laboratories. The Navy held a Conference on Marine Fog for participants in their research program in January of 1974. Coupled to evaluations of results from a literature survey, these three resources provide the main basis for the present report.

The basic fog processes are related to the methods of control in section A.2. The most effective current dissipation methods are identified in section A.3, and the basic problems which restrict operational effectiveness of the best methods are discussed in section A.4. A few observations and order-of-magnitude estimates are presented in sections A.4 and A.5 to indicate the nature of the phenomena in fog which are to be controlled. Each of the topics introduced in this chapter is treated in greater depth in subsequent chapters.

A.2 The Basic Fog Processes

A parcel of atmospheric air depends upon two basic factors for the initiation of fog:

1. Correct concentrations of nuclei upon which water vapor may condense, and

2. Water vapor concentrations which are large enough to initiate the condensation onto the nuclei.

Fog exists at about 100 percent relative humidity and droplet concentrations of from about 10 to 800 per cubic centimeter. The required initial concentration of water vapor depends upon the type of nuclei and upon the temperature of the water vapor. A nucleus which has a lower initiation water vapor concentration and an atmosphere which has a lower temperature both result in a droplet formation threshold at smaller concentration of water vapor.

In incipient fog conditions diffusional growth competition among nuclei for the available water vapor determines how many nuclei are activated. Once fog exists competition between droplets and added active nuclei can result either in a reduction in growth or evaporation of the original droplets. Depletion of fog droplets may also occur due to droplet coalescence or fallout for the larger droplets. The dominant factors in an increased rate of collision and coalescence of droplets are larger droplet diameters and greater relative velocities between droplets. The observed stability of fog in the natural state, in which ample water vapor exists to prevent droplet evaporation, depends upon initial activation of larger numbers of nuclei. This keeps the growth rate of each droplet low since the water vapor is shared with many droplets.

A fog is changed in either its incipient or developed states by changes in droplet and nucleus population properties and by changes in temperature and in water vapor concentrations. Any modification effort will have to change at least one of these basic parameters. The details of how they must or may be changed in particular micrometeorological situations are the essence of the modification problem.

A.3 Means of Fog Control: A Classification and Preliminary Evaluation

Means of fog control are listed in subsections A.3.1 and A.3.2 according to whether they produce or dissipate fog. Some overlap in this classification scheme exists in the sense that a process may be used to initially delay formation of fog but the final result may be a more dense and long-lived fog.

A.3.1 Developing and Maintaining Fog

Table A-1 lists methods which have been reported in the literature. An asterisk preceding the item number indicates that the method has been demonstrated to be clearly successful in atmospheric fog.

Table A-1

Methods of Developing and Maintaining Fog

*1. Addition of condensation nuclei (CN) to prevent or reduce droplet size spectrum shifts, direct growth to fallout sizes or collision-coalescence.

*2. Monolayer deposition on droplets for evaporation suppression.

*3. Water droplet spray-injection to saturate atmosphere.

 4. Cooling (effective in conjunction with 3).

 5. Monolayer doposition on droplets for temporary suppression of growth of droplets so that additional nuclei will be activated and the final fog state will be more dense and stable.

A.3.2 Prevention, Dissipation and Visibility Improvement

Many methods for clearing fog have been shown to be technically possible. Table A.2 lists the methods which have been found in the literature. Those whose item number is preceded by an asterisk have been found to be practical at least in a limited way.

Table A-2

Methods of Improving Visibility in Fog

1. Injection of water droplets for coalescence enhancement.

2. Injection of electrostatic charge on droplets for coalescence enhancement.

*3. Monolayer deposition on the underlying water surface for evaporation suppression.

4. Monolayer deposition on condensation nuclei to prevent activation.

5. Monolayer deposition on subfog droplets to prevent growth to fog sizes.

*6. Downwash and mixing of unsaturated air into fog to evaporate droplets.

7. Nucleation with surfactants to produce large droplets and both consequently and subsequently fewer droplets.

*8. Nucleation with hygroscopic materials to produce large droplets iwth same anticipated result as for 7.

*9. Nucleation with hygroscopic materials to produce evaporation of existing small droplets.

*10. Heating fog by jets of hot air to evaporate droplets.

*11. Heating fog by plumes of hot air to evaporate droplets.

12. Infrared heating of fog to evaporate droplets.

*13. Sonic agglomeration.

*14. Impaction sweeping.

15. Seeding with polyelectrolytes.

Of the methods listed above several offer promise which justifies additional research. Only two methods have high effectiveness and are fairly general in applicability at this time. They are nucleation by hygroscopic solids and heating by hot plumes.

Considerable advance in hygroscopic nucleation clearing of fog has occurred since the quite successful but costly method demonstrated by Houghton and Radford* in 1938. Briefly, the important advances in hygroscopic nucleation are as given in Table A-3.

Table A-3

Important Recent Advances in Hygroscopic Nucleation

1. Only a few tenths of a percent subsaturation of fog-particle-ambient air is adequate to clear fog rapidly.

2. Five to ten micron diameter NaCl particles are near optimum for relatively rapid (10 minute) clearing at moderate cost of nucleating material. Sizing is important for all nucleants.

3. Sodium chloride is the most cost effective nucleant, neglecting its corrosive nature.

4. Some organic substances, e.g., urea, are effective as noncorrosive and ecologically acceptable nucleants.

5. Mechanically fragile nucleants can be retained in a selected size range under operational conditions by use of encapsulation technology.

Despite the clear demonstration that hygroscopic nucleation dissipates fog, the method has proven to be insufficiently reliable in operational situations. The fundamental problem is that airflow and turbulence in the fog region transport and dilute the artificial nucleant concentration unpredictably. Consequently, those groups which need reliable clearing without much lag due to more research have turned to heating flame methods which are extravagant fuel users and are fire hazards.

A.4   Basic Problems Which Reduce the Operational Effectiveness of the Best Droplet Dissipation Methods.

A qualitative extended discussion of factors which prevent realization of the full potential of nucleation and heating follows.
Two factors interfere with successful operational use of the best principles.

1. Mass-cost effectiveness which considers facilities, logistics and hazards.

2. Transport (including mixing) of nucleants and heat by airflow and turbulence.

Current optimization of hygroscopic nucleation is based upon the need to balance the cost, weight and time required to clear fog against the uncertainty in knowledge of upstream trajectories ending at the target area at the right time. Artificial nucleant concentrations in fog are

---

*
The references are located after chapter 3.

found to be much less than planned. This is partly due to the fact that the character of the turbulent mixing is not known. Additionally the wind variation with height can spread the nucleant in undesired directions. When wind shear and turbulence are adequately measured or computed, the time variations in the mean flow field--e.g., meandering--may carry a properly treated patch of air at a different speed or direction than expected.

The cost of nucleant per cubic meter of treated air could be reduced by using significantly smaller particles. Perhaps a material could be found which is ten to one hundred times more effective in growing droplets. The latter is not likely and the former requires longer times to grow a droplet of a given size. At present, longer times of growth mean more uncertainty in dilution of the nucleant and proper arrival of the treated fog mass at the target. Thus the one micron nucleant must be spread over a greater fog area and the potential cost reduction is not realized while the operation becomes more extensive.

Operational emphasis is turning toward use of flame-heated plumes and jets to evaporate fog droplets. Here again additional knowledge of the influence of turbulence and airflow is required, but less urgently so.

A.5 Fog Characteristics and Related Processes: Some Estimates

Table A-4 and Figures A-1 through A-10 show some properties of fog and incipient fog conditions. It is important to note that no complete sets of parameter values exist for single fogs.

The graphs and calculations are presented (1) to demonstrate the existence of significant fluctuations from the mean state, (2) to provide a basis for further measurements which will permit or deny generalization and, (3) to illustrate the data currently available on fog properties.

Several process intensities and rates which are of interest with respect to fog production and dissipation are included in Table A-6. They provide a partial basis for evaluating the merits of possible fog modification methods, of fog parameter measuring instruments and of numerical and laboratory simulation schemes which are discussed in Chapters 1 through 5.

TABLE A-4

Some Reported Properties of Fog and Incipient Fog Atmospheres

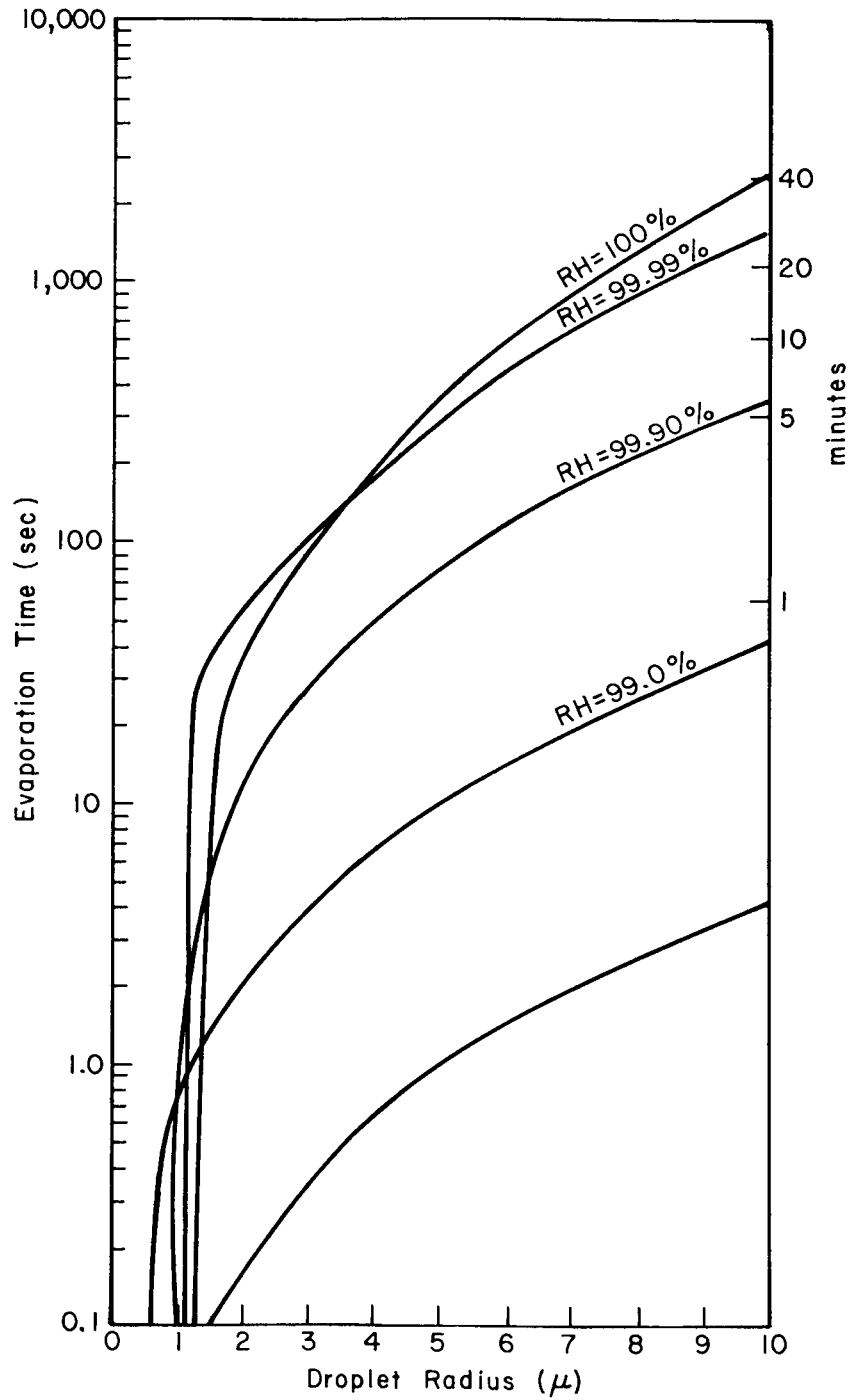|		radiation	advection	other
Liquid water content (g m^{-3})		.11	.17, .30 0.6 (dense marine)	
Vertical thickness — typical severe	(m)	0, 100 50, 300	0 200 200 600 150	
Horizontal	(m)	100	300 80	
Visibility — space Homogeneity — time	(m)	10 min		
Droplet concentration ($\frac{number}{cm^3}$)		200	40 (marine), 20 150	
Droplet diameter, mean (μm)		10	20,13,32 (dense marine)	
Droplet diameter, range (um)		5-35 5-15	10-60 24-120 7-65(dense marine) 10-30	
Nuclei sizes (μm)		0.08-0.8	0.1, 2-12(dense 70.5 marine)	
Nuclei type		Combustion Products	Coastal chlorides & nitrates	
(Expansion, water drop evap.) Saturation mechanisms (radiation,mixing, cellular convection)				
Turbulence Exchange coefficient K_m(m^2/s)			4	
Turbulence rms Vertical speed max (m/s)			0.3, 0.8 (Chu & Thayer) 1-2 (Pélie)	
Turbulence flux of vent velocity $u'w'$(m^{2}s^2)			~ 16x10^{-2}(Chu & Thayer)	
Wind speed (m/s)		0.5-4	0.5-10, 0.5+20	
Wind shear (s^{-1})			4x10^{-2} (Chu & Thayer)	
Static Stability $\frac{\partial\theta}{\partial z}$ ($\frac{K}{m}$)				
Water vapor content g Kg^{-1}			7.7 g Kg^{-1} 3-15 g Kg^{-1} limits	
Vertical gradient liqwater			$\frac{+0.5\ g\ Kg^{-1}}{100\ m}$ g $\frac{-.1+.2\ g\ Kg^{-1}}{100\ m}$ fog bottom fog top	$\frac{+1.5\ g\ Kg^{-1}}{100\ m}$ adv.**
Vertical gradient of droplet diameter				$\frac{-5.6}{100\ m}$ adv.**
Vertical gradient of droplet no density				$\frac{+250+500 cm^{-3}}{100\ m}$ adv.**
Av. length scale vertical eddies				
Max length scale vertical eddies			~ 200 m +	
Eddy spectra (in terms of length or time scales)				
Mean droplet diameter			Δt ~ 30 sec mode rms ~ 5μ*	
Liquid water content			Δt ~ 1 min rms ~ 0.04 gm^{-3*} mean ~ 0.08 gm^{-3}	
Droplet number density			Δt ~ 50 sec rms ~ 2 cm^{-3} mean ~ 8 cm^{-3}	
Maximum droplet diameter			Δt ~ 30 s: rms ~ 5/4* Δ ~ 90 s: rms ~ 10μ	
Eddy flux spectra Heat				
Water vapor Liquid water				
Cond. nuclei				
Flux of I.R. radiation energy				
Electric field gradient				

* Kunkel   † Pelie   ** Rogers, Mack & Pelie, 1972.

Fig. A-1 Evaporation times of droplet vs. relative humidity
(Assumed droplet nuclei - 0.1 radius NaCl particles).
(NASA HQ 1969).
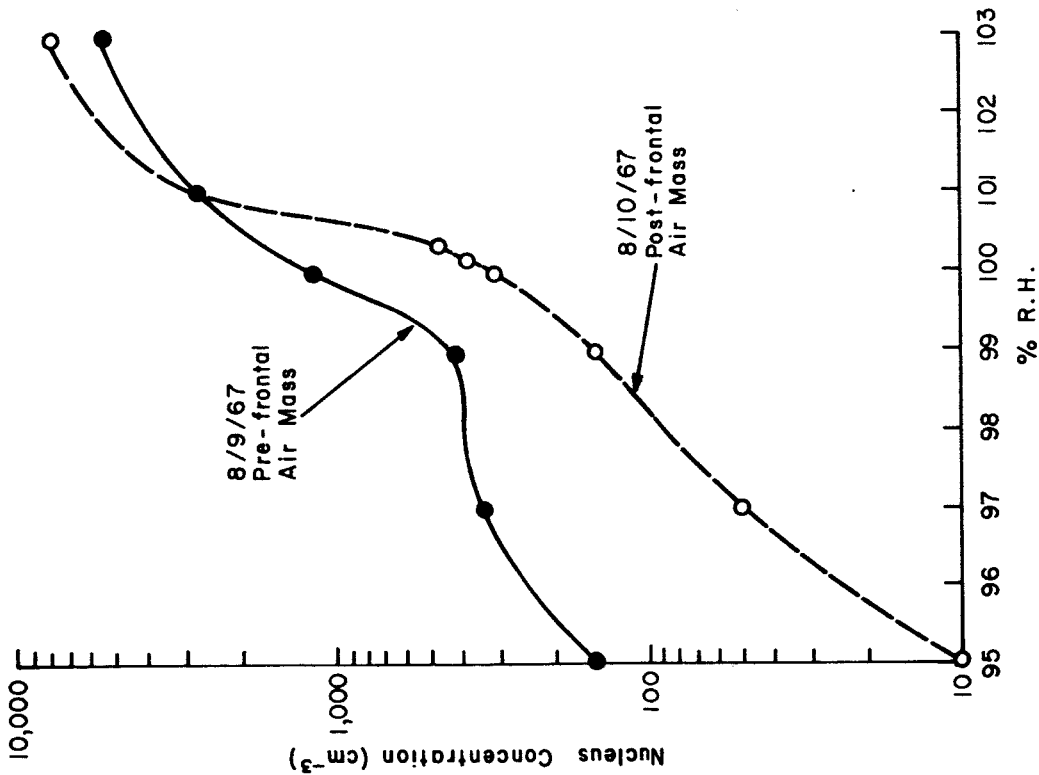
Fig. A-2 Concentration - R.H. spectra of active condensation nuclei for various fog and non-fog conditions (NASA Headquarters, 1969).
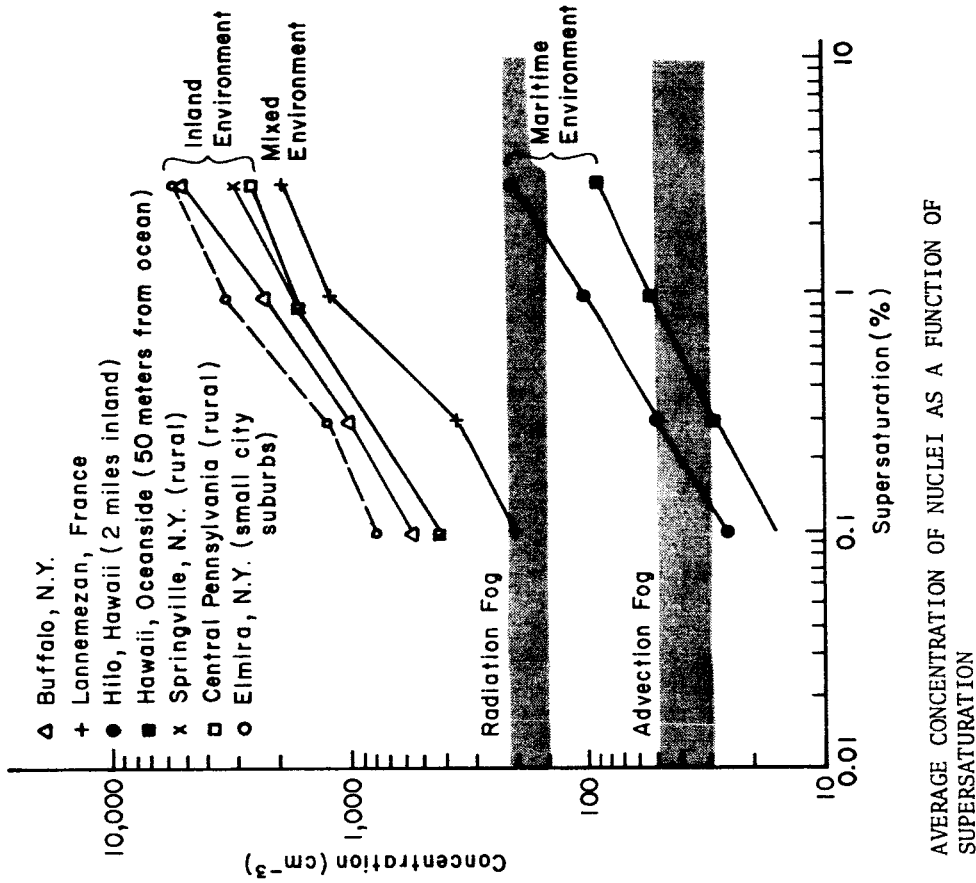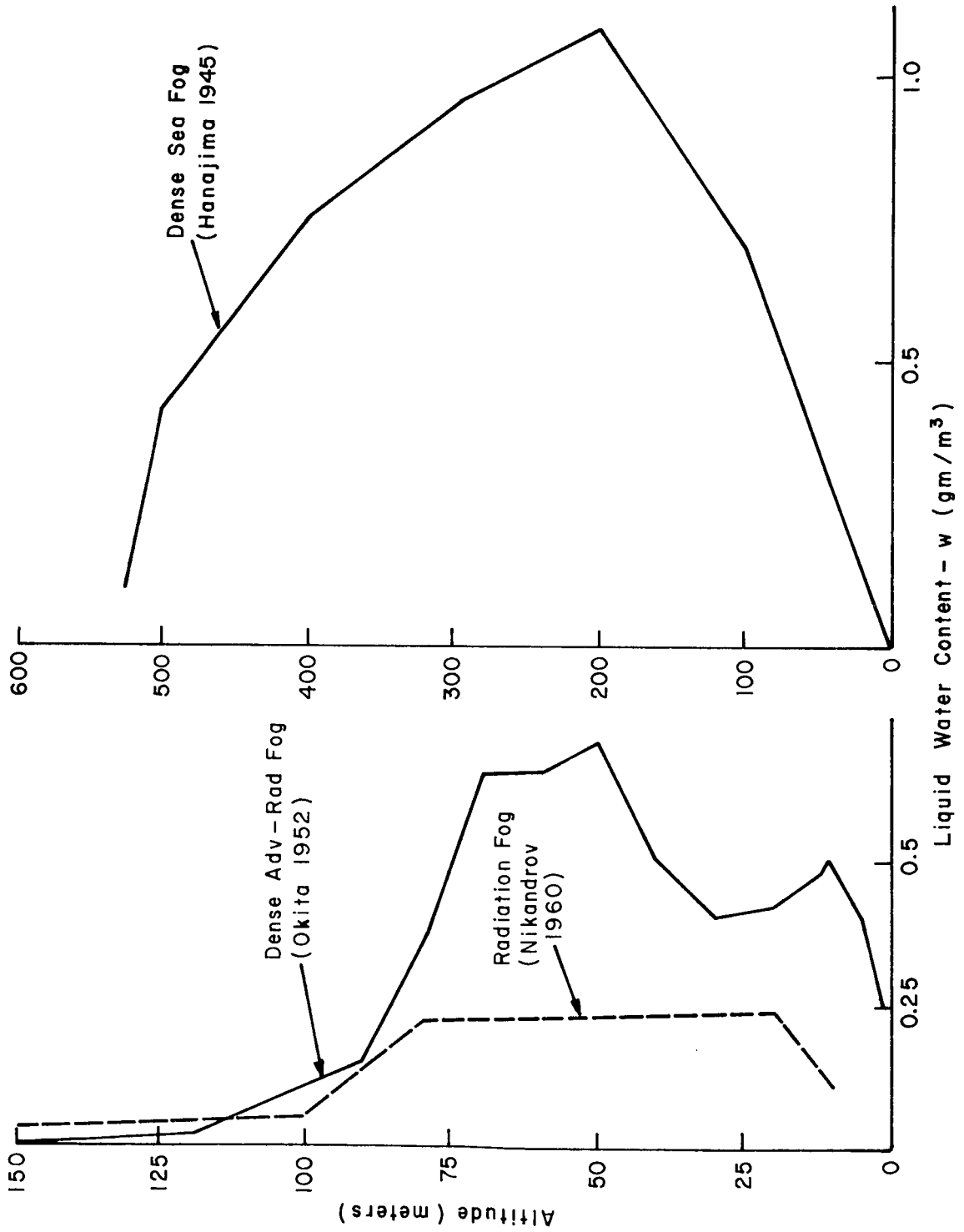
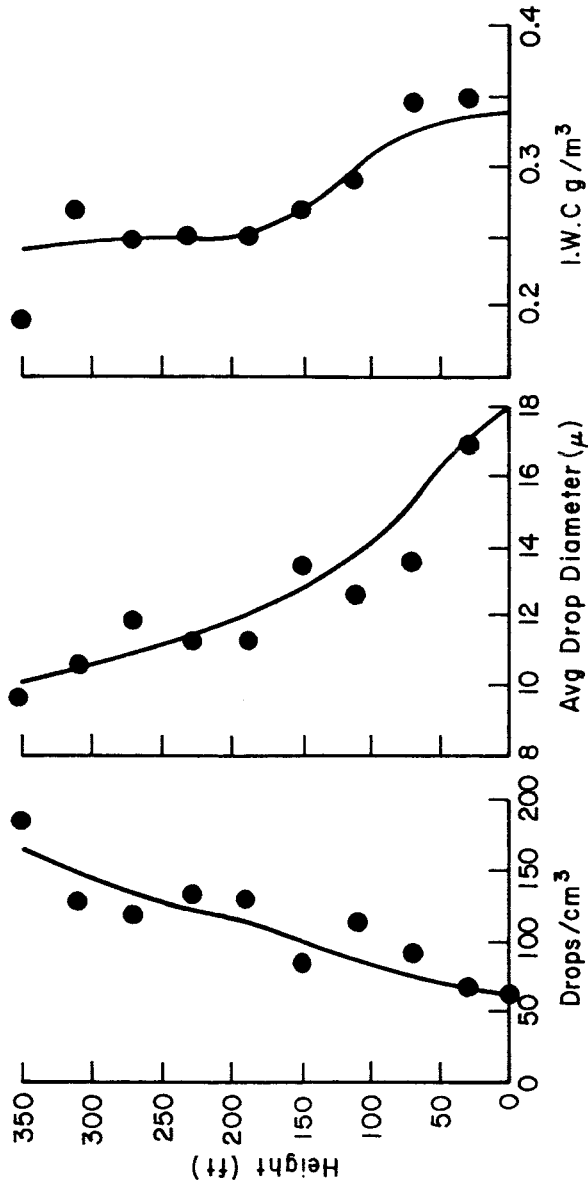Fig. A-3 Vertical variation of average liquid water content. (Jiusto, 1964)

Fig. A-4a Vertical profiles of valley fog parameters (Average data from four fogs)
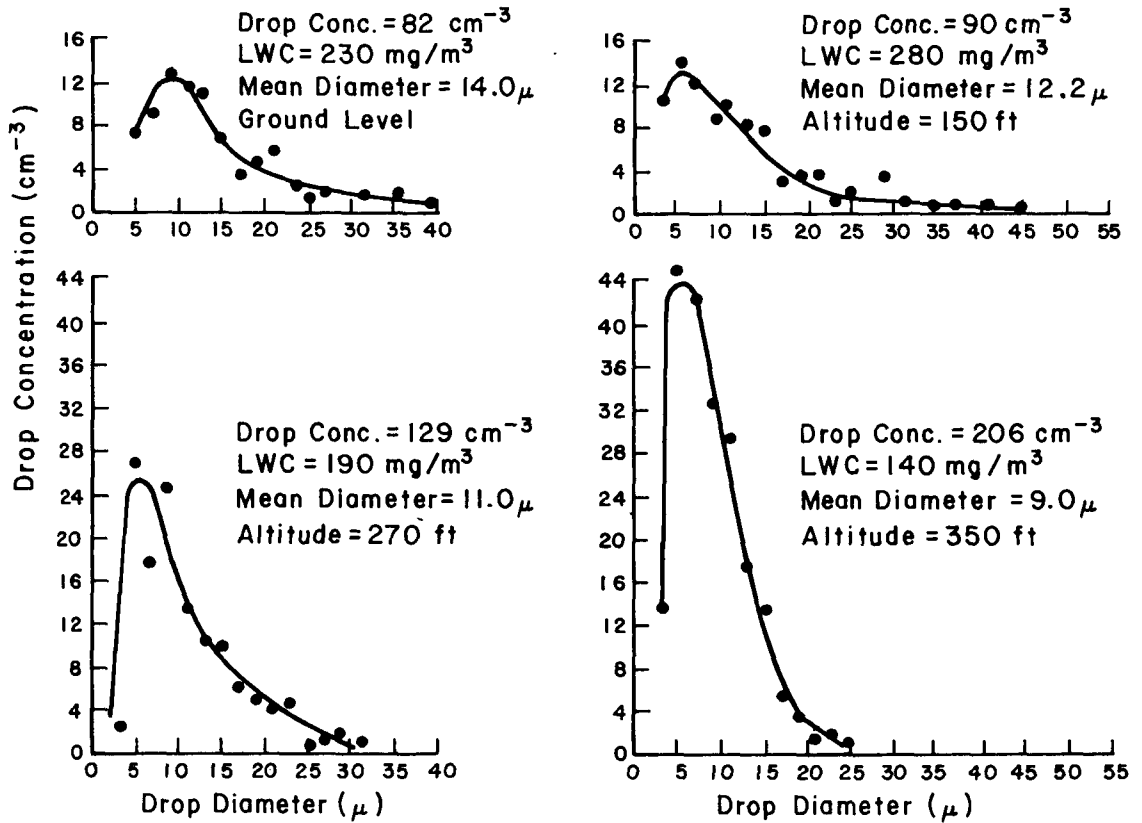Fog parameters vs. height (NASA Headquarters, 1969)

Fig. A-4b Drop size distributions at four levels in a valley fog,
Elmira, N. Y., 30 August 1968. Fog parameters vs. height
(NASA Headquarters, 1969).

CONTROL LOCATIONS

Transmissometers	Baseline
Horizontal surface - Upwind control	34 m
Horizontal surface - Downwind control	34 m

TARGET TOWER

Transmissometers	Baseline
Horizontal surface -	34 m
Vertical 1 m - 27 m	26 m
Vertical 26 m - 56 m	30 m

	Surface	7 m	16 m	31 m	46 m	56 m
Temperature	x	x	x	x	x	x
Dew point		x	x	x		x
Horizontal wind				x		x
Vertical wind		x	x	x		x
Drop sampler			x		x	
Gelman liquid water				x		

Table A-5　An example of the instrumentation used for one of the more complete fog studies (Rogers, Mack and Pilie, 1972).
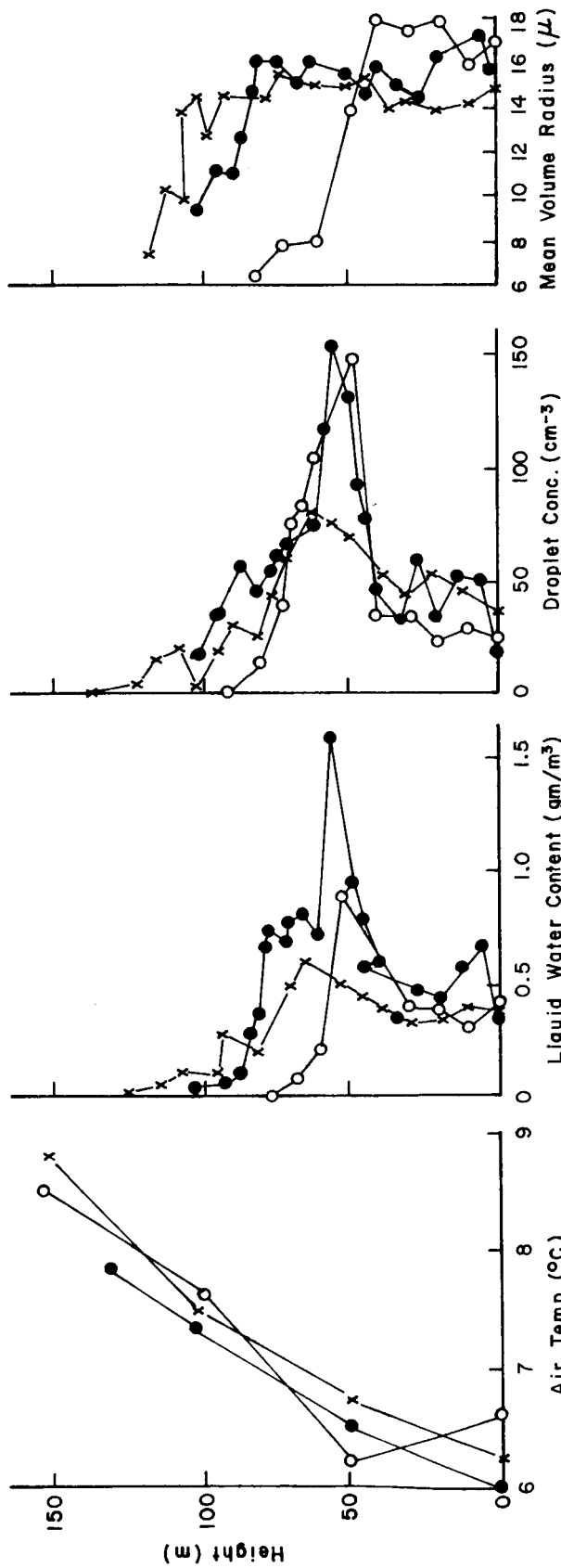
a-1 Temperature profiles on October 29, 1959.   0437-0450 JST; x0600-0609 JST;   0657-710 JST.

a-2 Vertical distributions of liquid water content on October 29, 1959.   29-1, 0359-0424JST: x29-2.
     0527-0552 JST: 29-3, 0625-0650 JST.

a-3 Vertical distributions of droplet concentration on October 29, 1959. For symbols see Fig. 16.

a-4 Vertical distributions of mean volume radius on October 29, 1959. For symbols see Fig. 16.
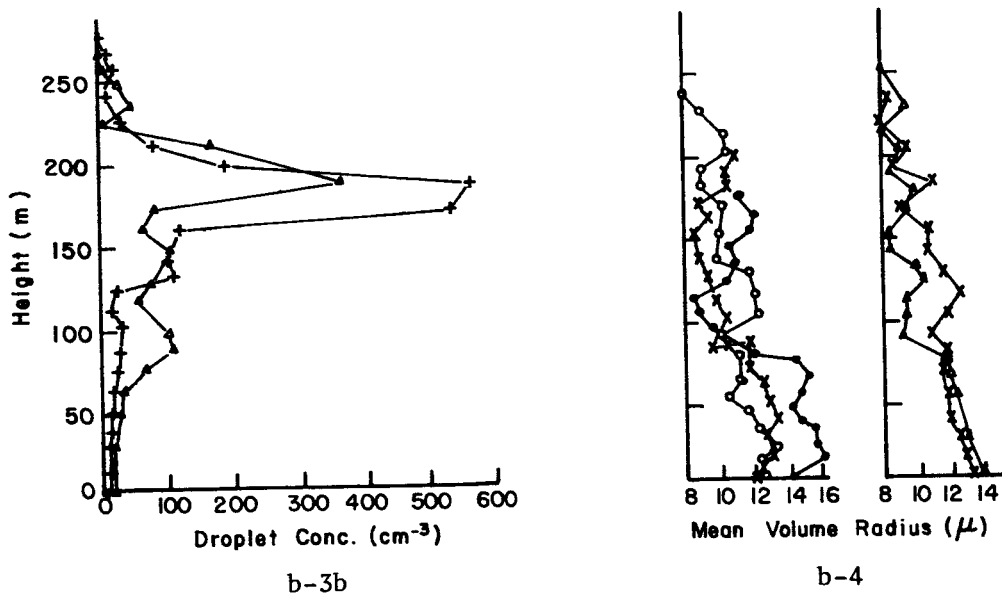
Fig. A-5a Time and spatial variations of parameters in advection-radiation
           fogs. Note: No wind and turbulence data (Okita, 1962).
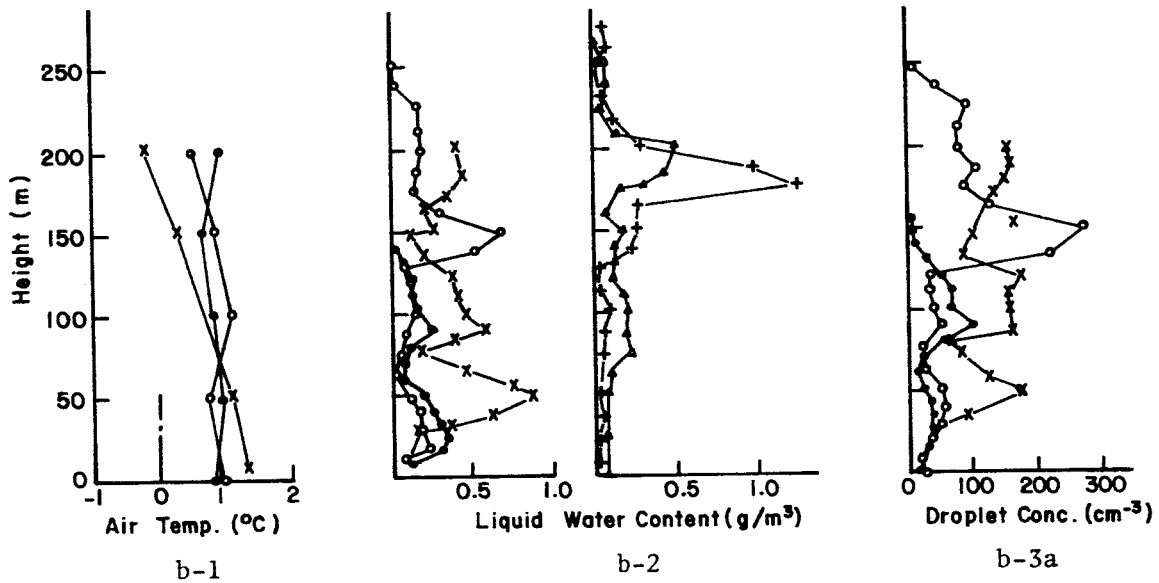
b-1 Temperature profiles on October 18, 1959.   0420-0438 JST:
          x 0535-0546 JST;   0712-0729 JST.

b-2 Vertical distributions of liquid water content on October 18,
      1959.   18-1. 0352-0417 JST; x 18-2, 0509-0534 JST;   18-3,
      0604-0629 JST; ÷ 18-4, 0644-0709 JST; Δ 18-5, 0848-0913 JST.

b-3a and b Vertical distributions of droplet concentration on
          October 18, 1959. For symbols See Fig. 4.

b-4 Vertical distributions of mean volume radius on October 18,
      1959. For symbols see Fig. 4.

Fig. A-5b Time and spatial variations of parameters in advection-
            radiation fogs. Note: No wind and turbulence data
            (Okita, 1962).
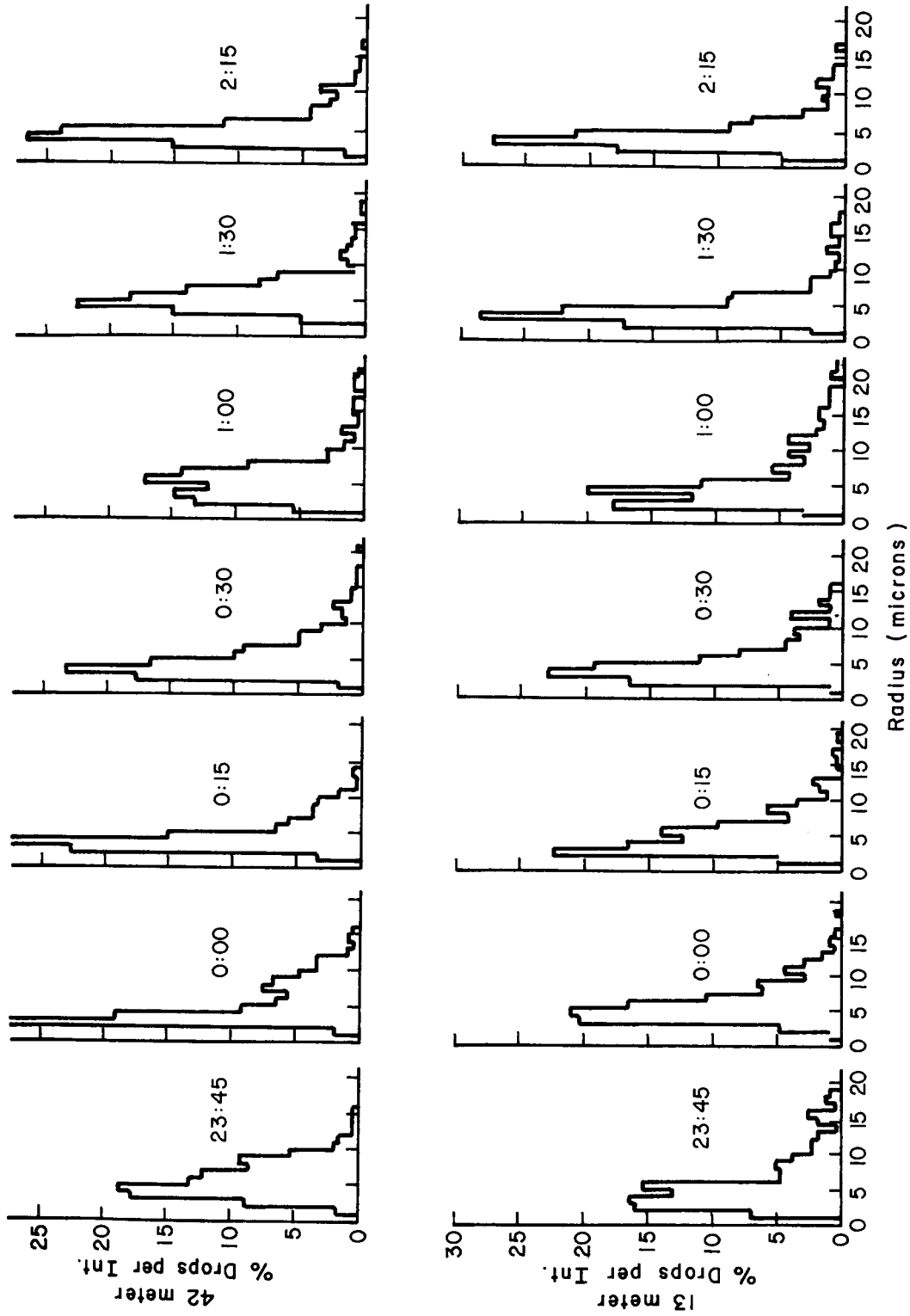
Fig. A-6   Drop size distributions obtained at two levels in unmodified fog: 29-30 July 1972 (Rogers, Mack and Pilie, 1972).
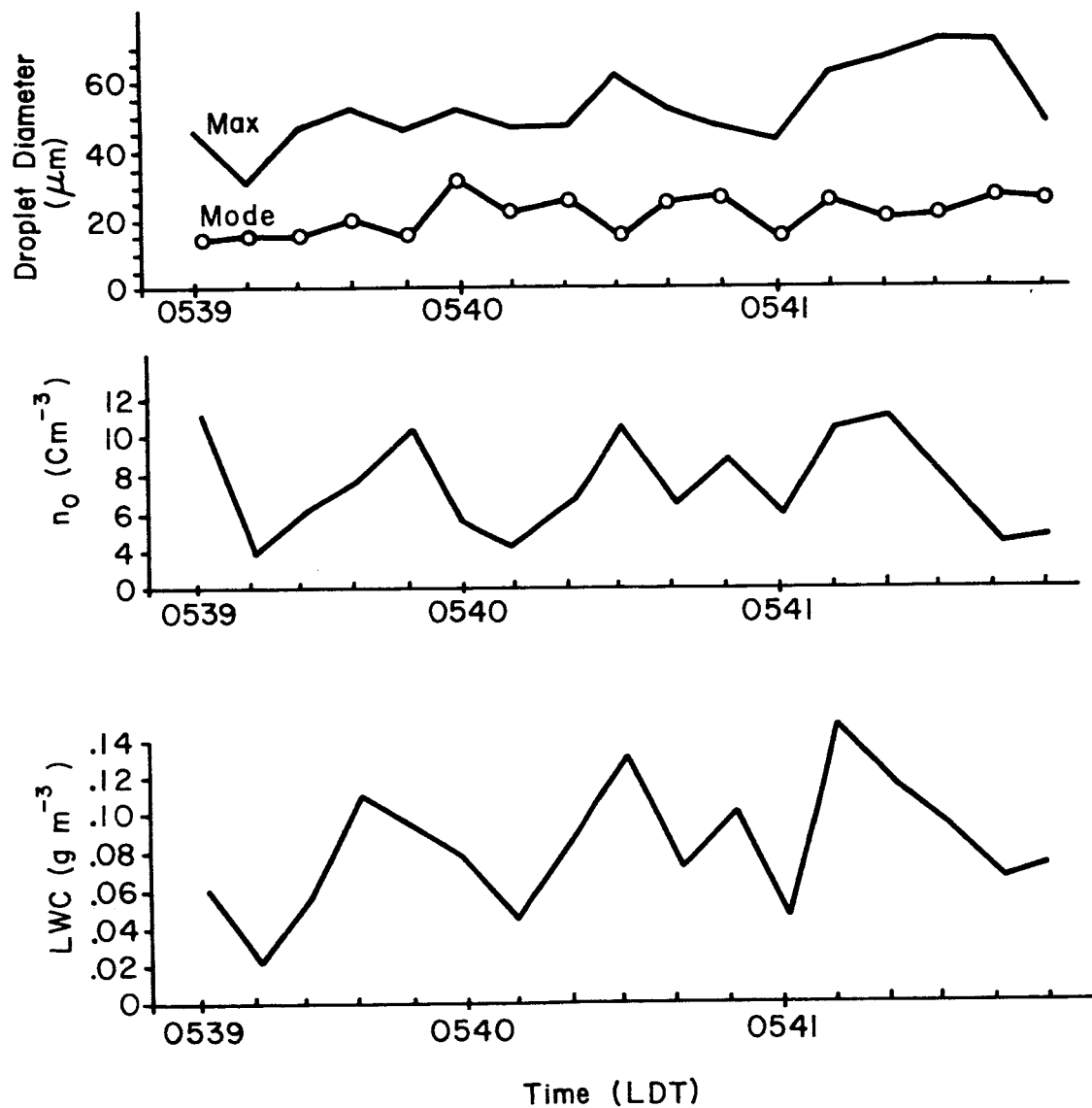
Figure A-7 Time variation of liquid water parameters in fog.
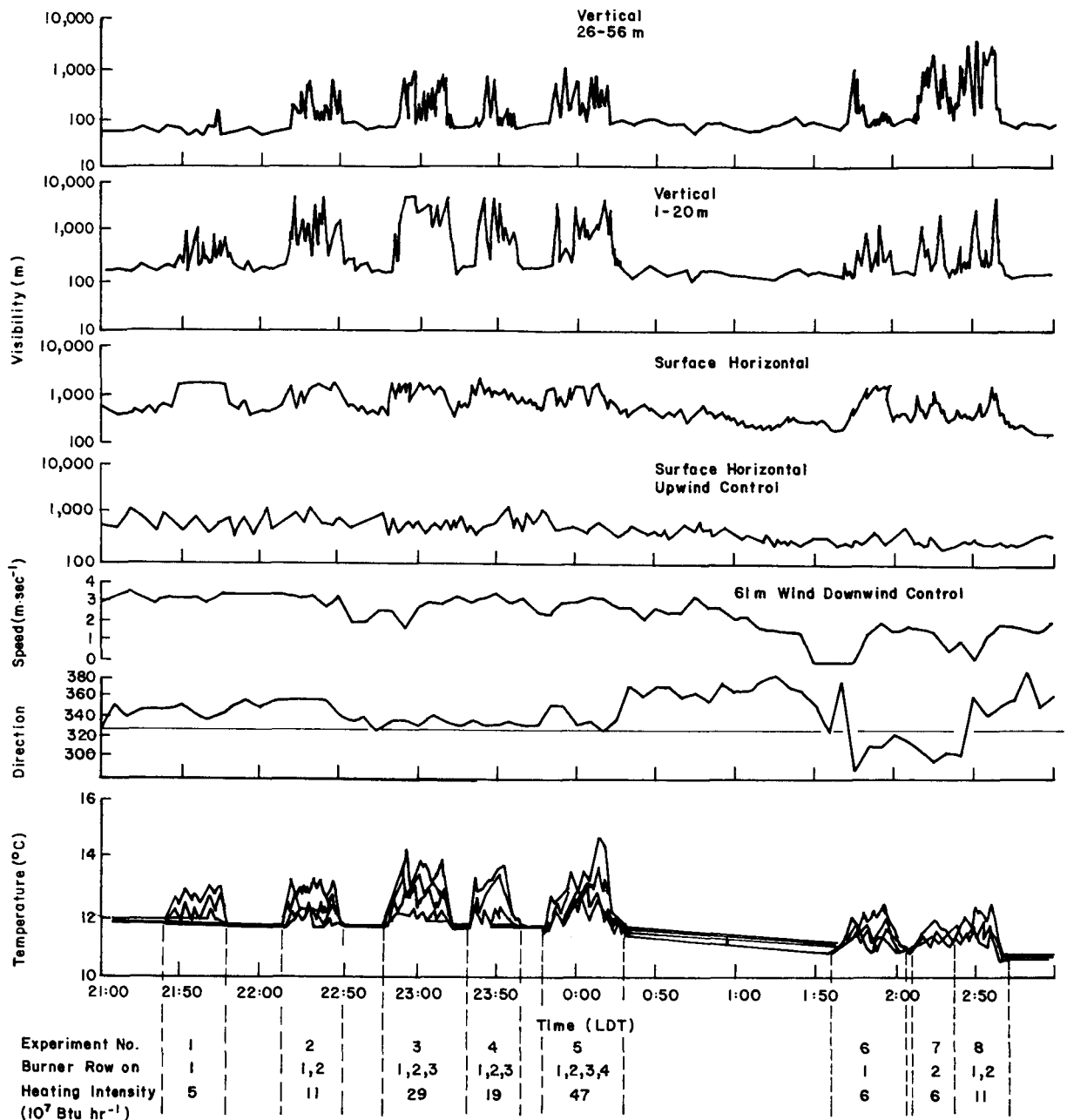(Adapted from Kunkel, 1971, p. 483 Table 1.)

Fig. A-8 Visibility, temperature and environmental wind for fog clearing experiments 11-12 July, 1972, Vandenberg, California. (Rogers, Mack and Pilie, 1972).
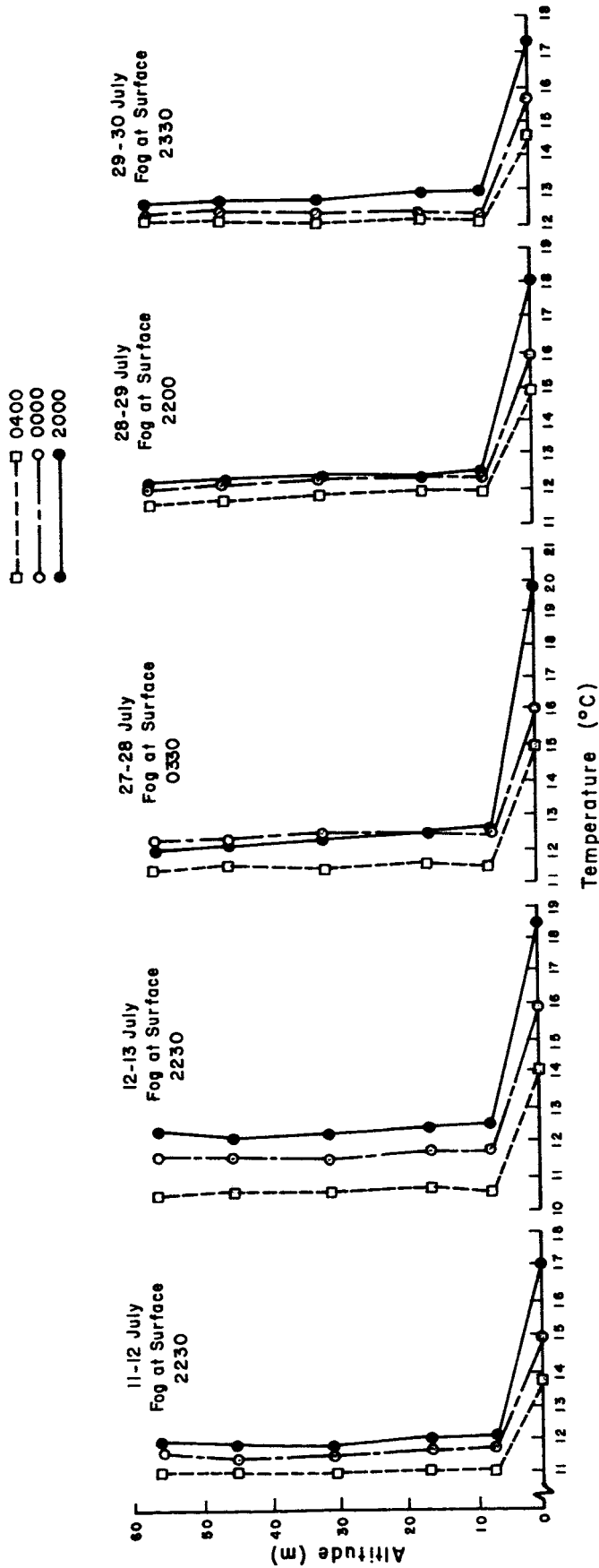
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Fig. A-9 Vertical profiles of temperature at indicated times in five Vandenberg costal fogs, July 1972 (Rogers, Mack and Pilie, 1972).
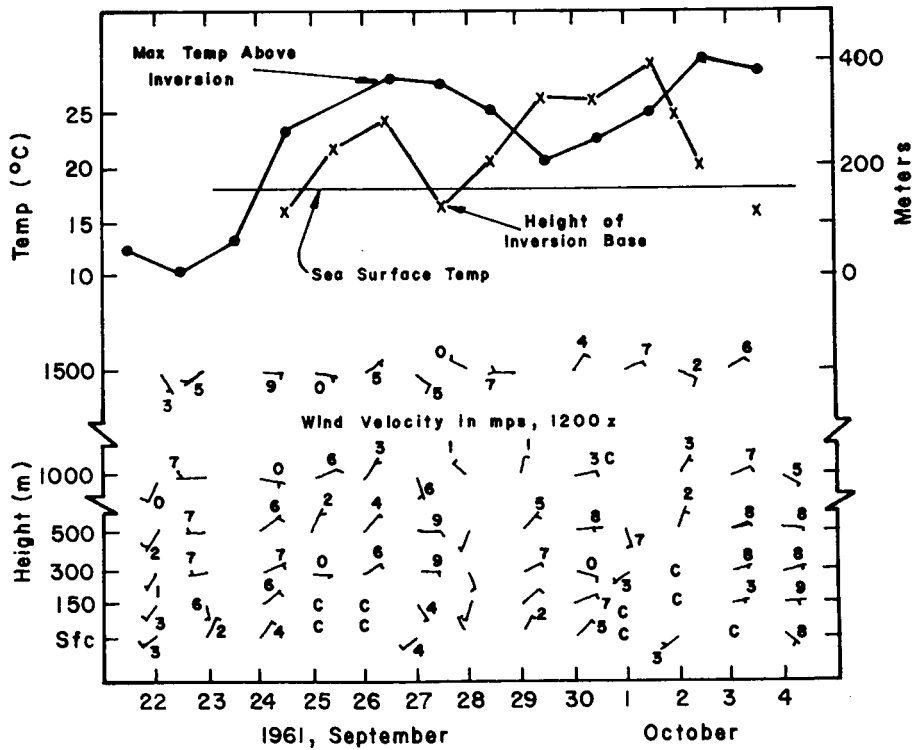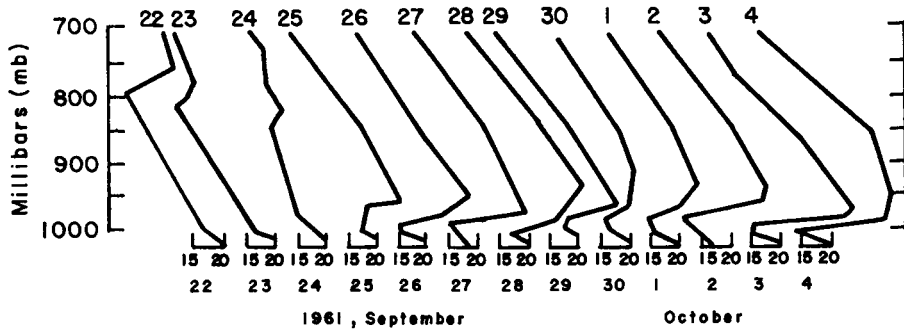
Fig. A-10 Daily sequence of static stability, inversion height
and surface wind velocity surrounding a fog event
(denoted by a solid bar). Adapted from Leipper,
1968.

TABLE A-6

Some <u>Crude</u> Estimates of Magnitudes and Rates of Some
Processes Related to Fog Physics and Fog Control

1. At warm fog temperatures the saturation mixing ratio is strongly
dependent upon the temperature.

$$\chi_s = 3 \text{ to } 15 \text{ g kg}^{-1} \text{ (g - water vapor)(kg - air)}^{-1}$$

$$\overline{\frac{1}{\chi_s}\frac{d\chi_s}{dT}} \sim 0.1 \text{ K}^{-1}$$

Then if initially $\dfrac{\chi_v}{\chi_s} \doteq 0.9$ (Rel. humidity = 90%) a decrease in
temperature of $\Delta T \doteq -1K$ will produce saturation by the method
$\chi_s \rightarrow \chi_v$.

2. Droplets freely falling through unsaturated air evaporate in
very short times. Consider T = 10C.

$$-\frac{dr}{dt}\Big) \text{ initial} \qquad\qquad \overset{\sim \Delta t}{\sim} \text{ vanishing time}$$

$\dfrac{\chi}{\chi_s}$	(d = 100μ)	(d = 10μ)	(d = 100μ)	(d = 10μ)
0.1	0.7 μs^{-1}	2 μs^{-1}	1 sec	0.05 sec
0.5	1.4 μs^{-1}	4 μs^{-1}	2 sec	0.1 sec
0.9	7 μs^{-1}	20 μs^{-1}	10 sec	0.5 sec

3. If water droplets evaporate in an air mass two effects bring
the condition closer to fogginess; added water vapor increases
χ_v and decreased temperature decreases the χ_v at which
saturation occurs, χ_s.

Evaporation of $\dfrac{1 \text{ g water}}{1 \text{ Kg air}} \Rightarrow \Delta T \doteq -2K$

$\Delta T = -2K \Rightarrow \chi_s = \chi_{s_i} - 2g \text{ Kg}^{-1}$

$$RH_f \equiv \frac{\chi_{v_f}}{\chi_{s_f}} = \frac{\chi_{v_i} + 1g \text{ Kg}^{-1}}{\chi_{s_i} - 2g \text{ Kg}^{-1}} > R.H._{initial}$$

3.   (continued)

If $\chi_{v_i} = 7g\ Kg^{-1}$, $\chi_{s_i} = 10\ g\ Kg^{-1}$ then evaporation of $1\ g\ Kg^{-1}$ water into the volume results in near saturation:

$$RH_f \doteq \frac{7 + 1}{10 - 2} = \frac{8}{8} = 1.0.$$

4.   Adiabatic expansion and compression modify the saturation water vapor concentration.

$$\left. \frac{\Delta T}{\Delta_p} \right)_{adiabatic} \doteq \frac{-.6\ \text{degree Celsius}}{-10\ \text{millibar}}$$

The expansion cooling approach to producing fog in the atmosphere can exist in two situations: (a) movement of an air mass rapidly inward across a cyclone scale low and (b) upslope movement of air on mountainous or great plains slopes to mountains. Radiation cooling often dominates over expansion cooling.

Subsidence of fog 200 meters at sea level would add heat equivalent to 0.2 degree Celsius. At $\chi_s = 10g\ Kg^{-1}$ this would evaporate about 0.2 g/Kg water which is about the total χ_{liq} in moderate fog.

5.   Introduction of hygroscopic nuclei into a fog volume rapidly lowers the ambient relative humidity.

A saturated solution of calcium chloride sprayed at a concentration of 2.5 g m^{-3} into a fog lowers the droplet ambient relative humidity to 90 percent.

6.   Trees, especially conifers, sweep out fog droplets by impaction on the needles. Collection efficiency of a 1 mm diameter sphere for 10 micron diameter droplets when the speed of relative motion is 4 m s^{-1} is 0.9. For 20 micron droplets the best collection is on about 1 mm spheres also and has an efficiency of 0.98. Needles on conifers are about 1 mm in diameter and are cylindrical instead of spherical. They are fairly effective collectors, especially when arrayed on trees to provide a three dimensional porous passage for foggy air.

1.7   A Turbulent Velocity Eddy Accelerates Flow

Due to gradients of acceleration and due to different droplet sizes turbulent fog should increase the rate of droplet growth by coalescence. A computation adapted from data in Green and Lane for NH_4Cl aerosol shows that the rate of coagulation of ($\sim 1\mu m$ diameter) particles is increased by factors greater than three in the first 30 seconds by turbulence (estimated by the author of this review) whose

velocity and length scale are about 0.5 m s^{-1} and 0.1 m, respectively. This turbulence may produce accelerations of about 0.5 g. The turbulence level is not much greater than might be found in fog. The particles in fog are perhaps 10 to 100 times as massive and are more likely to be induced to collide by turbulence.