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1.0 INTRODUCTION

Weather phenomena and environmental impact of chemicals have been clearly identified as major constraints to the agricultural aviation industry. These constraints impact unfavorably on current operations and impose threats to future operations. Operational procedures are strongly dependent upon meteorological parameters, since various combinations of wind direction and speed, air temperature, wind and temperature gradients, and relative humidity necessitate the use of many different droplet sizes, altitudes and general application techniques. If one also includes parameters such as the purpose for application and crop type, the decision to proceed or withhold application under various meteorological conditions grows more and more complex. Weather factors also modify aircraft performance which may, in turn, necessitate payload reduction and changes to normal in-flight procedures. The purpose of this report is to gather and review existing information related to the influence of meteorology on agricultural aviation and to begin a definition of the necessary experimental program required to fill the gaps in our knowledge and to provide an understanding of the effect of weather phenomena on operational procedures. The results of the study indicate that current knowledge relative to meteorological effects on aerial applications is sufficiently scarce that very little can be said with regard to operational procedures as dictated by weather conditions.

In addition to influencing operational procedures, damage caused by chemicals which were inaccurately applied create penalties that agricultural aviation operators must avoid. The accuracy with which a chemical can be applied is related to prevailing meteorological conditions. Environmental protection regulations will very likely begin to restrict agricultural aviation operations based on weather conditions. Primary among these restrictions are limitations of how much of the chemical will be allowed to drift onto neighboring areas. It is expected that environmental protection regulations will soon require measurements of meteorological conditions prior to aerial applications of the more hazardous chemicals. This study reviews some of the environmental protection regulations and illustrates the need for experimental measurements to provide a source basis for these regulations.

Also, the study points out that due to constraints such as availability of equipment or funds, no extensive, systematic study of meteorological conditions on spray dispersion has been carried out. There is a definite need for such a systematic, experimental re earch project to delineate, measure, and quantify the significant meteorological parameters which minimize agricultural chemical drift. Successful completion of such a project will help agriculture aircraft operators to apply the correct amount of chemical at the desired location necessary to increase food production and to reduce damage and contamination to nearby crops. An experimental project of this type will also help to differentiate under which meteorological conditions different types of chemicals may be applied without chemical residues exceeding EPA established tolerance levels. Meteorological data is also required to support the planned NASA agricultural aircraft flight research activities.

The report is organized as follows. A general review of the growth, potential benefits, and current procedures relative to agricultural aviation is presented in Section 2.0. Section 3.0 discusses the control of spray patterns and the different parameters which can affect the dispersion and control of agricultural chemicals. Section 4.0 is concerned with EPA regulations of pesticides and presents a brief table illustrating some of the current tolerance levels. Numerical models and the experimental data required to support their development are discussed in Section 5.0. Section 6.0 presents and discusses those meteorological parameters felt to be of significance in the dispersion of agricultural chemicals dispensed by aircraft. The approximate range of instrumentation capabilities required to measure these parameters are tabulated in this section. Section 7.0 provides a data matrix of previous work in the field of particle dispersion and lists the meteorological parameters which enhance the dispersion process. It is concluded in Section 8.0 that a systematic study of weather phenomena related to aerial applications is urgently needed and that this review provides the initial definition of the meteorological phenomena and variables of most significance. The results of the study serve as the starting point for a follow-on effort to fully define and plan an experimental program to develop the meteorological technology necessary to define weather operating envelopes and operating procedures. The results will also serve to develop an understanding of weather related environmental impact associated with aerial applications and to support the development of advanced aerial application technology.

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2.0 REVIEW OF AGRICULTURAL AVIATION

Agricultural aviation is a growing, dynamic segment of American industry. Its impact on United States farm production and the economy of the country is quite large relative to the size of the industry. The potential impact is even larger.

Aerial application presently makes a significant impact in many areas including seeding, fertilizing, insecticiding, herbiciding, and in various other forest and agricultural management techniques. The major contribution of aerial applications is agricultural support, primarily concerned with food production. The most scarce resource used in the production of food is land. This fact, plus the increasing world demand for food, indicates that increased return per hectare of land has and will continue to be of paramount importance in agricultural production. Average increases in grain yields per hectare since 1950 [1] are shown in Table 2-1. Although great improvement in yield has occurred since 1950, these statistics show that recent improvements have not been as spectacular as previous gains. Approximately 30% of the total agricultural yield is lost to pests each year. Improved aerial application techniques will help to recover some of this immense loss.

The use of agricultural aircraft and aerial application techniques are only one factor in the overall picture of agriculture development. Aerial application techniques are tools to be used to help increase yield when they are economically feasible. In some of the less developed countries, however, it may be too expensive, especially if they are dependent on small lot farming.

When using aerial application techniques, meteorological parameters such as wind velocity, turbulence, and temperature gradient can adversely affect the quantity of chemical deposited at the desired location [2]. At present, no comprehensive systematic study of how meteorological parameters affect chemical deposition dispersed by aircraft has been carried out. A better understanding of the effect of atmospheric movement on the transport of the wide range of particle sizes present in the drift of agricultural chemicals will help to insure better pest control and enhance yields in the future.

TABLE 2-1

AVERAGE U.S. GRAIN YIELDS, 1950-1974 (METRIC TONS/HECTARE) [1]

Grain	1950-54 Average	1955-59 Average	1960-64 Average	1965-69 Average	1970-74 Average
Wheat	1.16	1.49	1.70	1.85	2.11
Corn	2 47	3.05	3.92	4.93	5.31
Grain sorghum	1.22	1.77	2.68	3.32	3.39
Barley	1.50	1.59	1.82	2.26	2.27
Oats	1.22	1.39	1.57	1.81	1.80

The Research and Development Committee of the National Agricultural Aviation Association (NAAA) has performed an analysis which indicates that a 10 percent increase in farm production can be directly attributed to the use of aircraft [3]. The contribution of aerial application to increased farm productivity is understandably related to the increased use of fertilizers, insecticides, and herbicides. Table 2-2 [4] provides insight into present trends in aerial applications. The total area treated in the United States has increased despite only a moderate increase in the number of aircraft used. The trends in formulations used can also be observed in this table. In 1950, about 50 percent of the materials were applied as dusts and about 38 percent as sprays. By 1960, spray applications were ahead of dusts, and by 1970 low-volume and ultra-low-volume (ULV) spray techniques had almost replaced the more hazardous dust formulations [4]. Today 80 to 90 percent of all application materials are sprays. Ultra-low-volume spray techniques are, however, subject to potential drift hazards. Additional experimental data on the parameters affecting the drift of chemicals and their relative importance is needed.

Table 2-3 [5] provides additional information on aircraft usage during a five-year period. A 16 percent increase in the number of aircraft and a 26 percent increase in annual flight hours per aircraft occurred from 1970 through 1974.

TABLE 2-2

TRENDS IN MATERIAL FORMS AND USES OF AIRCRAFT APPLICATIONS, AREAS TREATED, AND NUMBERS OF AIRCRAFT [4]

U.S.A.	Percentage of Total Treatment Area (Hectares × Number of Treatments) 1950	1960	1970
Forms:			
Spray pesticides	38	46	75 (est.)
Dust pesticides	49	39	5
Granular pesticides	--	3	8
Fertilizer	6	5.5	7
Seeds	7	6.5	5
Uses:			
Agriculture defoliant	4	3.5	5 (est.)
Insecticide	--	73.5	59
Fungicide	--	1.8	8
Herbicide	--	12.7	18
Forest (insect)	--	2.7	3
Miscellaneous	5	6	7
Total hectares treated (millions)	16.2	29	42
Total number of aircraft	4500	5130	6100

TABLE 2-3

AGRICULTURAL AVIATION TRENDS IN THE UNITED STATES [5]

Year	No. of Aircraft	Miles Flown	Hours Flown	Hrs/Yr/AC
1970	5,802	134,674,676	1,395,711	241
1971	5,530	135,305,028	1,397,998	253
1972	6,338	156,608,948	1,615,687	255
1973	6,736	182,352,340	1,846,590	274
1974	6,916	189,241,771	1,892,586	274

Both fixed and rotary wing aircraft are utilized by the aerial-chemical application industry. The aircraft are usually flown in a crosswind with consecutive parallel swaths made into the wind. Depending on the application, flight altitudes are usually from several feet to several tens of feet. In terms of meteorological parameters, the following preliminary observations can be made. First, since at greater flight heights, the horizontal wind velocity will be greater (assuming the norma increase in wind speed with altitude which is typically logarithmic), a higher potential is created for drift downwind of the swath area. Second, greater flight heights result in droplets having greater fall distances, and therefore once again the drift potential is increased because of the greater time available for the droplets to be acted upon by the horizontal wind. Third, at greater flight heights parameters such as relative humidity and temperature have a greater time to affect droplet size. The most common effect is to decrease droplet size, thus increasing the fall time which then results in a greater drift potential. Fourth, at times temperature inversions are found within a few feet of the crop canopy. Chemicals dispensed below or above such an inversion will not be able to easily penetrate the inversion layer. Chemicals dispersed above the inversion will diffuse upward while the majority dispensed below the inversion will eventually settle on the vegetation being treated. At first thought, it appears most advantageous from a drift standpoint to keep flight heights as low as possible.

Other factors, however, must be considered. Pilot safety is a prime consideration. The type of crop being sprayed, the meteorological conditions, and plant coverage desired, in turn, dictate flight height. Aerial-chemical application of row crops is usually performed with the spray nozzles several feet above the crop canopy. The average height of the spray nozzles above the crop canopy is commonly referred to as the boom height. Spray deposition of chemicals in and around crops other than row crops, however, may require different flight heights, since a lower flight height may not result in the optimum deposition of the chemical. For example, with all other conditions constant, lower flight heights usually result in narrower swath widths and higher chemical concentrations. Therefore, one must consider the overall result desired before making a decision on flight height.

A literature search has revealed that the range of operating velocities for agricultural aircraft in the United States is approximately 60 to 125 mph for fixed wing aircraft (turbine powered aircraft are working at speeds as high as 150 mph). Newer aircraft may work at even higher speeds. Rotary wing aircraft, on the other hand, perform aerial applications at various speeds, 10 to 60 mph, and in certain cases while hovering. Droplet size distributions produced by spray nozzles, in turn, are affected by flight speed. At high flight speeds smaller drop size distributions are usually produced. Smaller drops are influenced to a greater extent by the local meteorological conditions than are larger drops because they can be carried further by the wind and are dispersed more rapidly by turbulence. Flight speed may, therefore, need to be chosen in conjunction with local meteorological effects to achieve optimum aerial applications.

Since the conception of aerial application around 1920, there have been only slight changes in the fundamental design of dispersal equipment. Liquid materials are usually applied with a system comprised of a wind-driven spray pump (i.e., pump which operates with no auxiliary power from the aircraft) and a circular dust spray boom, which is mounted beneath or behind the aircraft wing. Solid materials are usually applied with a venturi device which utilizes ram-air pressure to accelerate the material laterally and thus effect a wider swath [6]. Depending on whether a liquid or solid material is being applied, a spray boom (usually spray nozzles distributed along a tubular duct) or device to accurately spread dry materials over the swath width desired is installed on the aircraft.

Agricultural aircraft have a number of technical and economical advantages over surface machines for use in large-scale farming. The primary reasons for the growth of agricultural avaiation are: mounting labor costs, increases in the number of treatments of each crop, speed of application, and ability to make the application without physically entering the crop area. A Wall Street Journal article expressed the advantages of ag-air very well [7].

> Farmers who use ag-airmen say one factor is that it is almost impossible to get competent help to spread pesticides by ground. One airman can cover 100 acres with herbicides in an hour--a task that often takes a ground rig all day. . . .
>
> Additionally, aerial application usually causes little or no crop damage. Soil compaction, which hurts crop growth, is avoided. When crops are rotated, aerial seeding can be done even before the previous crop is harvested, allowing the seeds extra time to germinate. Planes can spread fungicides on earth too wet to support ground machines.

The advantages of aerial application are numerous, but problems do exist. A drift hazard exists with any machine dispensing chemicals, both surface as well as aerial. With the aerial application of certain chemicals, the possibility of their drift onto sensitive crops poses a serious problem. Such losses with aerial procedures can be greater than for ground procedures due to aircraft induced turbulence and variation of meteorological conditions with height. The local meteorological conditions are probably the single most important factor controlling the success or failure of an aerial application operation. Basic meteorological parameters such as temperature gradient, wind direction, wind speed, velocity gradient, and relative humidity are all known to affect the rate of dispersion of materials released from aircraft equipment [8, 9]. However, the mechanism by which each parameter interacts with the spray has not been clearly identified. Carefully controlled field experiments are needed to understand these mechanisms if aerial application operations are to achieve maximum effectiveness.

Agriculture aviation problems also include those related to the aircraft, the distribution system, and the flow field (which includes the atmosphere as well as terrain and crop characteristics). Effects of meteorological parameters and flight path control on distribution accuracy are representative of areas where improvements are possible. Improved aircraft swath guidance systems will enhance the ability of the aerial applications operator to apply chemicals more effectively and accurately. Other aircraft research efforts are being directed toward improvements in wake interactions of drag reduction, propulsion efficiency, corrosion control, cockpit environmental safety, and dry material dispersal systems. These research efforts must go hand in hand with experimental investigations of meteorological parameters. The individual aircraft components may be developed and tested in wind tunnels, but the final relationships need to be established in well instrumented field studies.

Advances in aircraft liquid dispersal systems are dependent on one major factor, the effect of droplet size on distribution accuracy. The size of a droplet affects fall time and the evaporation rate as well as the effect of wind on the droplet during descent. A worthwhile effort would be to develop nozzles which provide monodisperse droplets. Other dispersal system research efforts should include: eliminating leakage and spillage, developing improved plumbing and valves, developing corrosion resistant materials, and designing loading and handling equipment that is efficient and which provides a greater measure of safety.

The aircraft flow field is another example of a factor which affects distribution accuracy. The development of improved aerodynamic designs for both the aircraft and material distribution systems is needed to minimize the adverse effects of the flow field on distribution accuracy. Other flow field factors affecting distribution accuracy which warrant research include weather phenomena such as wind shear, the nature of the crop, and the characteristics of the terrain being treated.

The process of chemical drift during spraying or dusting depends on three factors: the operation of the machine and its equipment, the physical form of the chemicals being applied, and the weather conditions in the precipitation zone of the droplets or particles after their ejection from the dispersal system. A better understanding of the meteorological parameters influencing aerial applications is essential to improve distribution accuracy.

Akesson and Yates summarized the problems posed by weather conditions for ag-air operators:

> The applicator must 'live with' the weather and try to confine his application to those times when wind velocity, direction and gradient, ambient temperature and temperature gradient, and relative humidity are favorable. Operationally this can be frustrating to the commercial applicator, who must try to accomplish the job to be done frequently in spite of less favorable weather. [2]

At times, the weather is so unfavorable as to preclude operations altogether. Elaborating on these weather factors, Akesson and Yates point out that for various combinations of wind directions and speed, air temperatures, wind and temperature gradients, and relative humidities, there are more favorable and less favorable droplet sizes, delivery altitudes, and general application techniques. Add, too, the variables of crop type and/or reasons for application (air/ground pesticides, leaf covering, ground fertilization), and the decisions to proceed or withhold application under various meteorological conditions grow more and more complex.

Meteorological research is needed to determine the most appropriate weather conditions to carry out aerial-chemical operations and to help determine the best altitude and flight path to use to improve chemical distribution over the crop and avoid drift of the chemical onto other sensitive crop areas. Also, in order to avoid hazardous health conditions, meteorological inputs are required for determining the diffusion of the spray or dust under various atmospheric conditions.

The foregoing review of agriculture aviation illustrates that qualitatively the dispersal of pesticides and fertilizers from aircraft is known to depend strongly on meteorological parameters. The exact mechanism by which these factors influence drift, droplet evaporation rate, particle coagulation, spray trajectory and interaction with the canopy, etc. and the degree of their individual influences are not quantitatively understood. Well designed field studies requiring, in some cases, unique instrumentation are needed to develop this understanding if continual improvement in agricultural production through the use of aircraft is to be achieved. Obviously, meteorological factors also correlate with the control of applications and the development of environmental protection regulations. These topics are described in the following chapters.

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3.0 SPRAY PATTERN CONTROL

Lack of control of spray patterns is a major obstacle to safe and effective aerial applications of agricultural chemicals. Effectiveness of treatment is often limited because of meteorological conditions and inadequate spray coverage resulting from the use of large drops. Crop damage and contamination may also occur when small drops drift from the target area. Preliminary investigations [1] into the relationships of drop size to spray drift, and the number of drops produced per unit of volume of spray applied, indicate that drops in the size range of 100 to 400 microns diameter are of the optimum size to reduce drift while still achieving adequate spray coverage.

Depending on the physical state and mechanical properties of the chemical, microbiological, or other preparations used in aerial operations there are three methods for application: dusting, scattering of granular materials, and spraying. Each of these application methods are affected differently and to a different degree by the local meteorological conditions. For example, granular materials, due to their size and weight, are not significantly effected by the local meteorological conditions, on the other hand, small dust particles may drift up to several miles causing crop damage and contamination. Final decision as to what are "satisfactory" meteorological conditions will depend not only on the use for which the preparation was prepared, but also on the physical characteristics of the preparation.

Dusting refers to the application of finely dispersed powdered preparations. The powder particles are characterized by small size and an irregular shape, which under conditions of high humidity, promotes coagulation and the formation of aggregates. For various powdered pesticides, the size of the individual particles is 1 to 20μm in diameter. A number of mineral fertilizers are also released in the form of powders, but as compared to pesticides they are more coarsely ground and have a particle size of 500 to 1000μm and greater [2].

The convenience of working with individual preparations ready for use and the high concentration of active material in powders (and hence the possibility of applying a small discharge per hectare) contributed to the acceptance of aerial dusting as the main method of application in the first stages of agricultural aviation. However, large losses of chemicals in the dusting process due to unfavorable meteorological conditions and poor chemical retention on dry plants has led to the replacement of this method by spraying and to some extent by granular scattering.

Scattering various granular materials, primarily dry mineral fertilizers, has also become widely used in aerial-chemical operations. Granular materials are characterized by the significant size of the particles as compared to powdered pesticides. Mineral fertilizers can be in crystal form, in the form of coarse powder, and granulated with particle sizes from 1 to 4 mm in diameter [2]. The significant size of the particles contributes to their rapid settling to the ground. Coarse, granular material falls principally beneath the aircraft and does not significantly drift from the on-target swath width.

Today spraying is the most widely used method for aerial-chemical application. Early sprays were applied using large amounts of diluent per hectare, with most of the spray droplets having greater than 400μm diameter. The introduction of more finely atomized, concentrated sprays having droplet diameters less than 300μm brought both advantages and disadvantages [3].

The choice of droplet size for field spraying is at best a compromise. On the one hand, ultra-low-volume (ULV) applications of small droplets of less than 50μm diameter have been shown to result in higher chemical effectiveness than larger droplets. Ultra low volume is another name for concentrate-type aerosol sprays; it covers a wide range of volumes and dilutions from a fraction of an ounce to a pint or more per acre. Dilution of chemical preparations with water or organic solvents decreases their chemical and/or biological activity thereby reducing their chemical effectiveness. Evaporation of these small droplets, due to low humidity, is also significantly reduced when using concentrated chemical preparations.

The relationship between the size of drops and their number when a given volume of liquid is being applied is that: the finer the drops, the greater the number that can be obtained. An increase in the number of drops can, in turn, provide a thicker and more uniform covering of the plant surface. Wind conditions in and near the top of the crop canopy also play a major role in plant coverage. Selection of the optimum particle size for effective coverage of a particular plant will depend upon the wind field and turbulence characteristics in and near the crop canopy. The development of an understanding of how the droplets or particles collect on the foliage will require a detailed study of the motion of the air about the foliage and the sensitivity of this motion to climatic conditions. Considerable work is required in this area.

Although small droplet sizes are desired for these reasons, one disadvantage is that the smaller droplets have greater drift potential (see Figures 3-1 through 3-4). A second disadvantage is that smaller droplets have a smaller linear momentum which affects a droplet's ability to impinge upon a surface. For a droplet to reach the plant surface, it must have sufficient momentum to penetrate the accompanying airstream which flows around the plant surface. If a droplet nears the plant surface with insufficient momentum, the centripetal acceleration imparted to it by the viscosity of the deflecting airstream changes its direction of velocity enough to cause it to travel parallel to the surface and depart with the airstream. Since momentum varies directly with mass and velocity, the smaller droplets of a spray spectrum may not impinge unless they have high velocity.

After leaving the aircraft, the velocity of a small droplet or particle is a vector quantity depending on nozzle orientation relative to the aircraft, the local flow velocity, and the initial particle velocity. This velocity is quenched by the resistance of the opposing airflow, the particle falls into the turbulent zone behind the aircraft, and then lags behind the aircraft.

The settling of fine particles or drops discharged from an aircraft is explained by the small mass of the particles and, consequently, by their small kinetic energy and the air viscosity. A rough analysis of particle trajectories ejected from an aircraft can be made by using a number of simplifying assumptions. The particle is assumed to be spherical and not to experience rotational or oscillatory motions and the air medium is assumed to be fixed.

For a rough calculation of the vertical steady-state settling rate of fine particles assuming the above conditions, one can use Stoke's formula:

$$V_d = \frac{4gr^2(\rho_\ell - \rho_a)}{18\eta} = 2\rho_\ell gr^2/9\eta = 1.2 \times 10^6 r^2 (\text{at } 1013 \text{ mb, } 20°\text{C})$$

where V_d (in actual atmospheric conditions the velocity enters as a vector which is at a finite angle from the normal to the surface) is the steady-state settling rate of the particle, m s^{-1}; g is the acceleration of gravity (9.8 m s^{-2}); η is the viscosity of air, kg $m^{-1}s^{-1}$; ρ_ℓ is the liquid density, kg m^{-3}; ρ_a is the air density, kg m^{-3}; and, r is the particle radius, m. The liquid density ρ_ℓ (water) is much greater than ρ_a (air); consequently, ρ_a can be neglected in the above equation. V_d will be less in an updraft and greater in a downdraft. The settling velocity in the atmosphere is actually the particle velocity minus the wind velocity. Stoke's formula is, however, valid for calculating the fall velocity of spherical particles in stationary air with a radius of 20μm or less. Drag coefficients (C_D) of rigid spheres and, hence, relations between $C_D Re$ and Re (Reynolds number) for larger drops have been determined experimentally [4]. Table 3-1 [4, 5] shows a compilation of experimentally determined terminal fall velocities. The results indicate that Stoke's law overestimates the actual terminal velocity in air for droplets larger than 20μm. For droplets of radius 40μm the actual velocity is already 10 percent smaller than the corresponding Stoke's velocity. Stoke's law for the drag is tolerably accurate for most purposes when the Reynolds number (Re) is less than 0.1. A 40μm radius droplet falling at terminal velocity in air has a corresponding Reynolds number of 0.930. The conditions for which Stoke's law analysis may accurately be applied, in the case of water droplets in still air, is restricted to droplets less than 20μm diameter.

TABLE 3-1

TERMINAL VELOCITIES OF WATER DROPS IN STILL AIR
(PRESSURE 1013 mb, TEMPERATURE 20°C) [4,5]

Drop Diameter (mm)	Terminal Velocity (cm s^{-1})	Re†	Drop Diameter (mm)	Terminal Velocity (cm s^{-1})	Re†
0.01	0.3	---	1.80	609	731
0.02	1.2	0.015	2.00	649	866
0.03	2.6	---	2.20	690	1013
0.04	4.7	0.120	2.40	727	1164
0.05	7.2	0.240	2.60	757	1313
0.06	10.3	0.410	2.80	782	1461
0.08	17.5	0.930	3.00	806	1613
0.10	25.6	1.690	3.20	826	1764
0.12	34.5	2.740	3.40	844	1915
0.16	52.5	5.550	3.60	860	2066
0.20	71.0	9.400	3.80	872	2211
0.30	115.0	22.800	4.00	883	2357
0.40	160.0	42.300	4.20	892	2500
0.50	204.0	67.500	4.40	898	2636
0.60	246.0	97.500	4.60	903	2772
0.70	286.0	132.000	4.80	907	2905
0.80	325.0	172.000	5.00	909	3033
0.90	366.0	218.000	5.20	912	3164
1.00	403.0	267.000	5.40	914	3293
1.20	464.0	372.000	5.60	916	3423
1.40	517.0	483.000	5.80	917	3549
1.60	565.0	603.000	---	---	---

†Calculated values. For D < 1.0 mm, the terminal velocities are based on the measurements of Beard and Pruppacher [4]; for layer drops, the terminal velocities are those of Gunn and Kinzer [5].

Steady-state conditions are, however, rarely present in the atmosphere. When turbulence and wind variation effects on the particle are taken into account, the governing equation of particle motion is considerably more complicated. Soo [6] gives the general equation of motion for a spherical solid particle as

$$\frac{4\pi}{3} a^3\bar{\rho}_p \frac{d\bar{U}_p}{dt_p} = \frac{4\pi}{3} a^3\bar{\rho}_p F(\bar{U} - \bar{U}_p) - \frac{4\pi}{3} a^3 \frac{\partial p}{\partial r} + \frac{1}{2}\frac{4\pi}{3} a^3\bar{\rho} \frac{d}{dt_p} (\bar{U} - \bar{U}_p)$$

$$+ 6a^2\sqrt{\pi\bar{\rho}\bar{\mu}} \int_{t_{po}}^{t_p} d\tau \frac{(d/d\tau)(\bar{U} - \bar{U}_p)}{\sqrt{t_p - \tau}} + F_e$$

where $\bar{U}$, $\bar{U}_p$ are velocities of the fluid and the solid particle ($\bar{U}$ is the mean velocity of the fluid encountered by the particle, not the distributed fluid around the particle); a is the particle radius; $\bar{\rho}$, $\bar{\rho}_p$ are the densities of the fluid and solid particle; F_e is the external force due to potential field; p is the static pressure; t is the time; $\bar{\mu}$ is the viscosity of the fluid material; and, F is the time constant (inverse relaxation time) for momentum transfer due to drag force, or

$$F = \frac{3}{8} C_D \frac{\bar{\rho}}{\rho_p} a^{-1} \left|\bar{U} - \bar{U}_p\right|, \ \text{sec}^{-1}$$

and the drag coefficient C_D is given by: $C_D = C_D(N_{Re})$, and the Reynolds number N_{Re} is given by $N_{Re} = 2av\bar{\rho}/\bar{\mu}$. The results shown in Table 3-1 cannot be directly related to atmospheric conditions, but should serve as an indication of the average relative magnitude of particle settling velocities.

Along with consideration of the vertical settling rate of particles, there is also interest in the horizontal path over which the ejected particle can move until it is "stopped" by the opposing air current. The maximum horizontal path of a particle with an initial velocity (V) can be calculated using the following formula:

$$S_{max} = \frac{\rho_d d^2 V}{18\eta}$$

where S_{max} is the maximum horizontal path of the drop; ρ_d is the density of the drop; d is the drop diameter; and, η is the absolute viscosity of the air.

The initial horizontal velocity of a small particle is quenched in the air within a fraction of a second, and such a particle, even for large initial velocities, can move only tens of centimeters until it is "stopped" by the opposing air current [2].

Under calm conditions of the surface layer of air (very unlikely), a drop or particle will fall vertically under the effect of gravity and there will be no drift. The time required for the settling of droplets from the same height will differ depending on the size of the droplets. If there is a wind during the settling time, droplets released from a height, H, will be carried a distance, L, in the direction of the horizontal wind velocity component, W, where $L = HW/V$. Figures 3-1 through 3-4 illustrate the horizontal distance which could be traveled by several different diameter droplets dispensed from different heights under different horizontal wind conditions. The terminal velocities, V, used for each droplet diameter were taken from the experimental values of Beard and Pruppacher [4]. The effect of droplet evaporation has not been included. Horizontal wind velocity was also assumed to be constant.

The horizontal wind velocity, however, normally increases with altitude being effectively zero at the ground. Particles will, therefore, be subject to different wind conditions as a function of height. The relationship between the horizontal wind velocity and altitude is dependent on several different parameters. Generally, the log profile is valid and the relationship between horizontal wind velocity and altitudes can be expressed as

$$\overline{W}(z) = \int_0^{L/V_d} \frac{\overline{W}_{ref}}{\kappa} \left(\frac{\ln\left(\frac{z + z_o}{z_o}\right)}{\ln\left(\frac{z_{ref} + z_o}{z_o}\right)} \right) dt$$

where $\overline{W}_{ref}$ is the velocity measured at a particular reference height; κ is von Karman's constant; z_o is the surface roughness; z is equal to

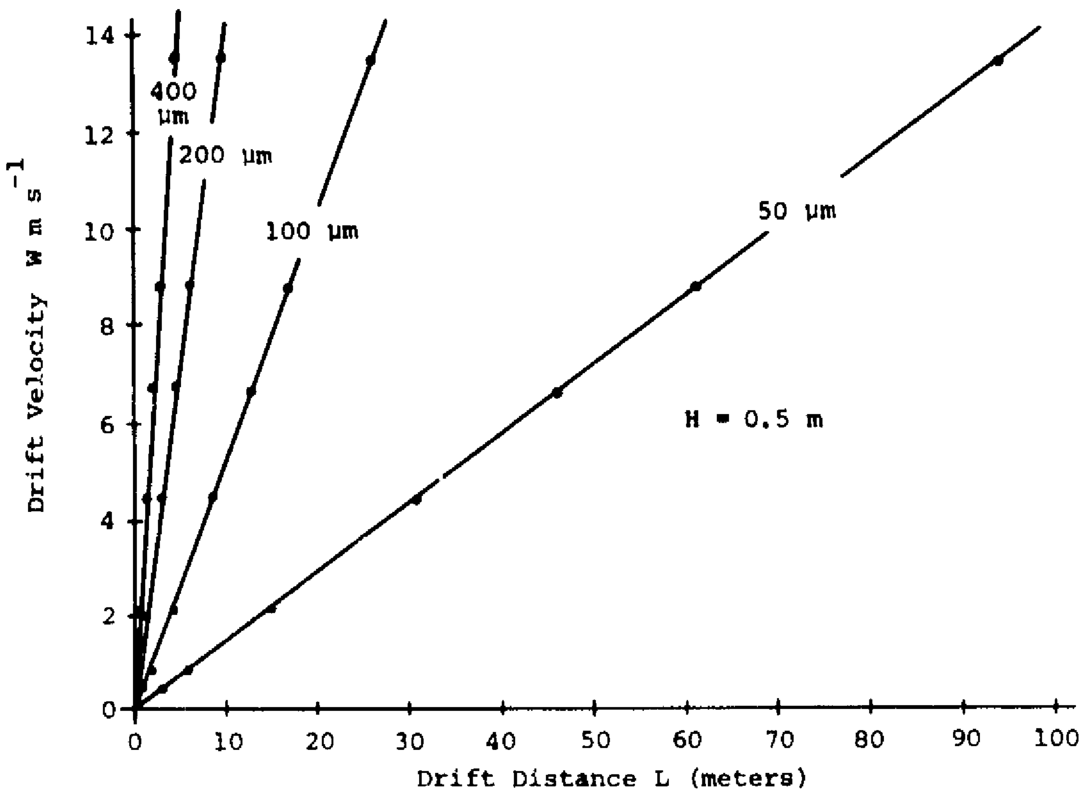

Figure 3-1 Graph of Drift Velocity Versus Drift Distance. Dispensing Height 0.5 m

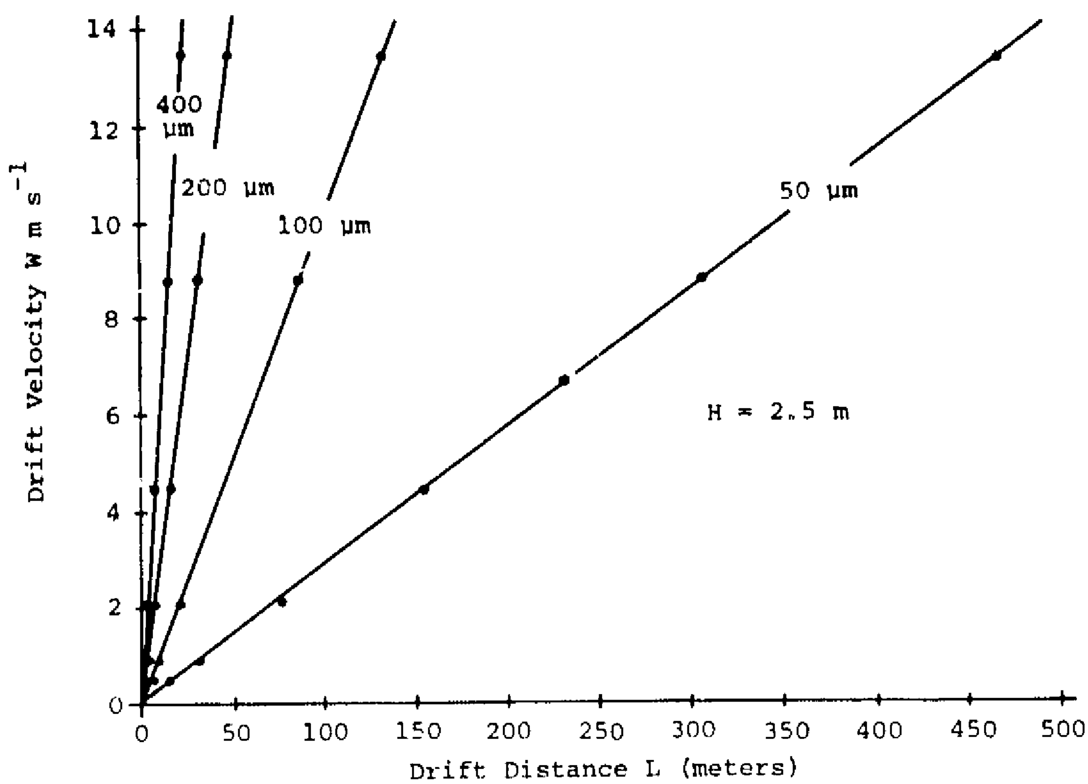

Figure 3-2 Graph of Drift Velocity Versus Drift Distance. Dispensing Height 2.5 m

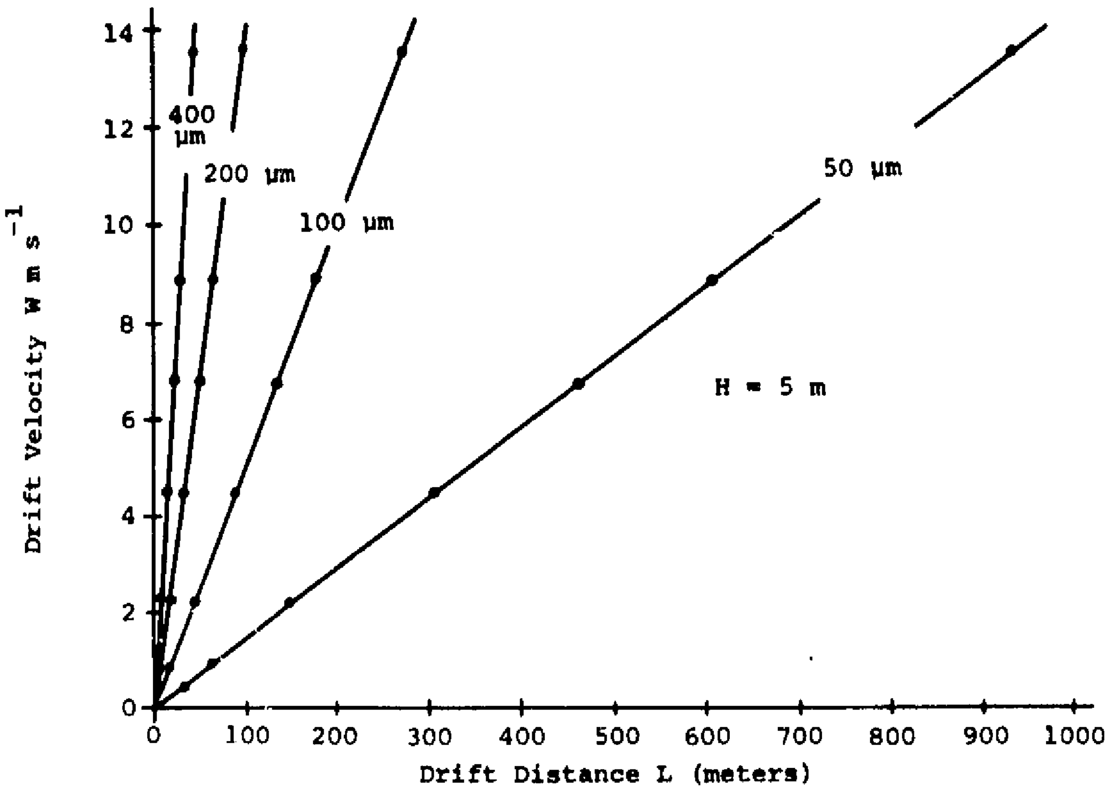

Figure 3-3 Graph of Drift Velocity Versus Drift Distance. Dispensing Height 5.0 m

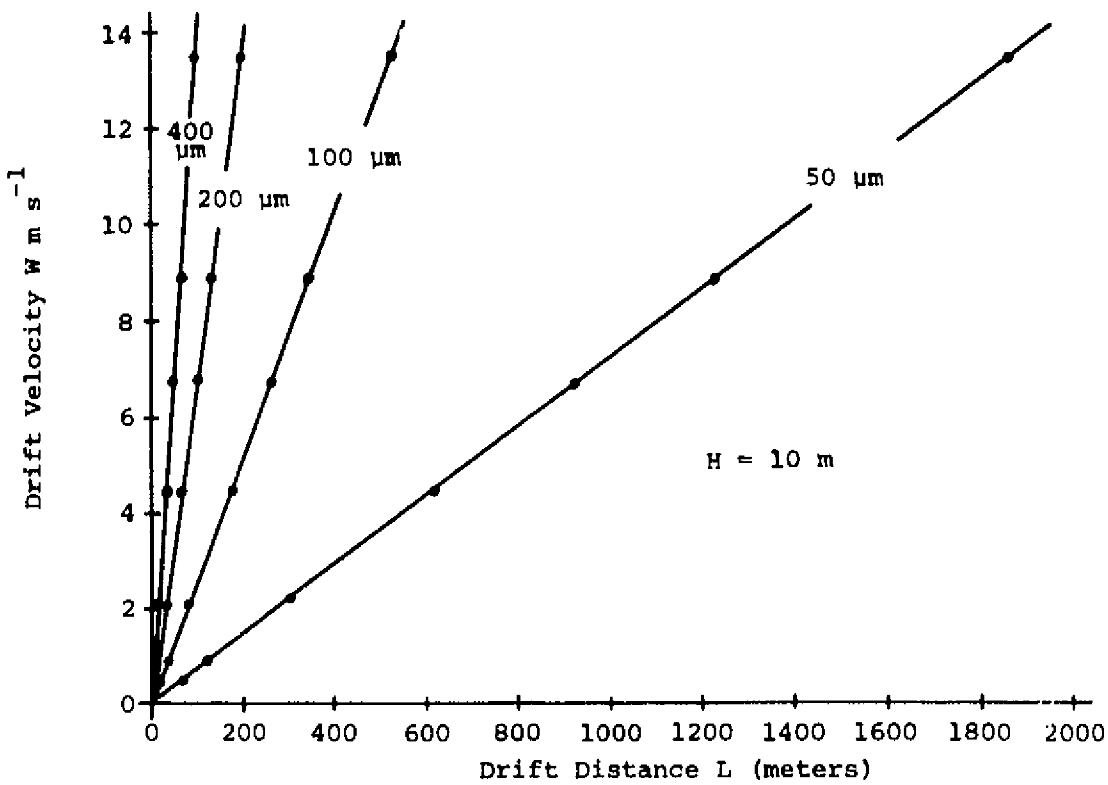

Figure 3-4 Graph of Drift Velocity Versus Drift Distance. Dispensing Height 10.0 m

$L - V_d t$; and, t is the time. Experimental measurements to delineate the effects of the parameters in this relationship would help to accurately assess particle drift potential at a particular spray site. It should be noticed that the horizontal wind profile depends on where one measures the wind speed. Figure 3-5 [7] shows several typical wind profiles which illustrate that the horizontal wind profile is dependent on the surface roughness, z_o. Figures 3-6 and 3-7 illustrate that flow over surface features such as a row of trees or a plateau can also appreciably affect the horizontal wind profile [7]. Thus, effective spray operations require an understanding of the true wind velocity and its spatial variation in the settling zone. In turn, an understanding is required of how such factors as the surface roughness and terrain features, both upwind and at the spray site, affect the wind characteristics. Experimental measurements to adequately assess the effects of these factors on spray dispersion will ultimately be needed. The results illustrated in Figures 3-1 through 3-4 cannot be directly related to atmospheric conditions, but serve as an indication of the average relative drift distances of different size particles.

The figures illustrate that smaller droplets have greater drift potential. Also, they show that as the dispensing height increases, the drift distance also increases. For example, a 50μm diameter drop released at a height of 2.5 meters with a 10 m s^{-1} horizontal wind travels approximately 350 meters whereas a 100μm diameter drop travels only 100 meters. A 50μm diameter drop released at a height of 10 meters, however, will travel approximately 1400 meters when subject to the same horizontal wind conditions.

Figure 3-8 shows the effect of relative humidity on drift for different drop sizes [8]. The graph illustrates that even in mild wind conditions (0.5 m s^{-1}), droplet sizes 200μm or larger are needed for accurate deposition. It also points to the fact that droplets larger than 200μm will probably be necessary to minimize the effects of drift.

Analysis of the above graphs, Figures 3-1 through 3-8, shows that several meteorological parameters are important in drift hazard analysis. First, spray drift is proportional to the horizontal wind velocity

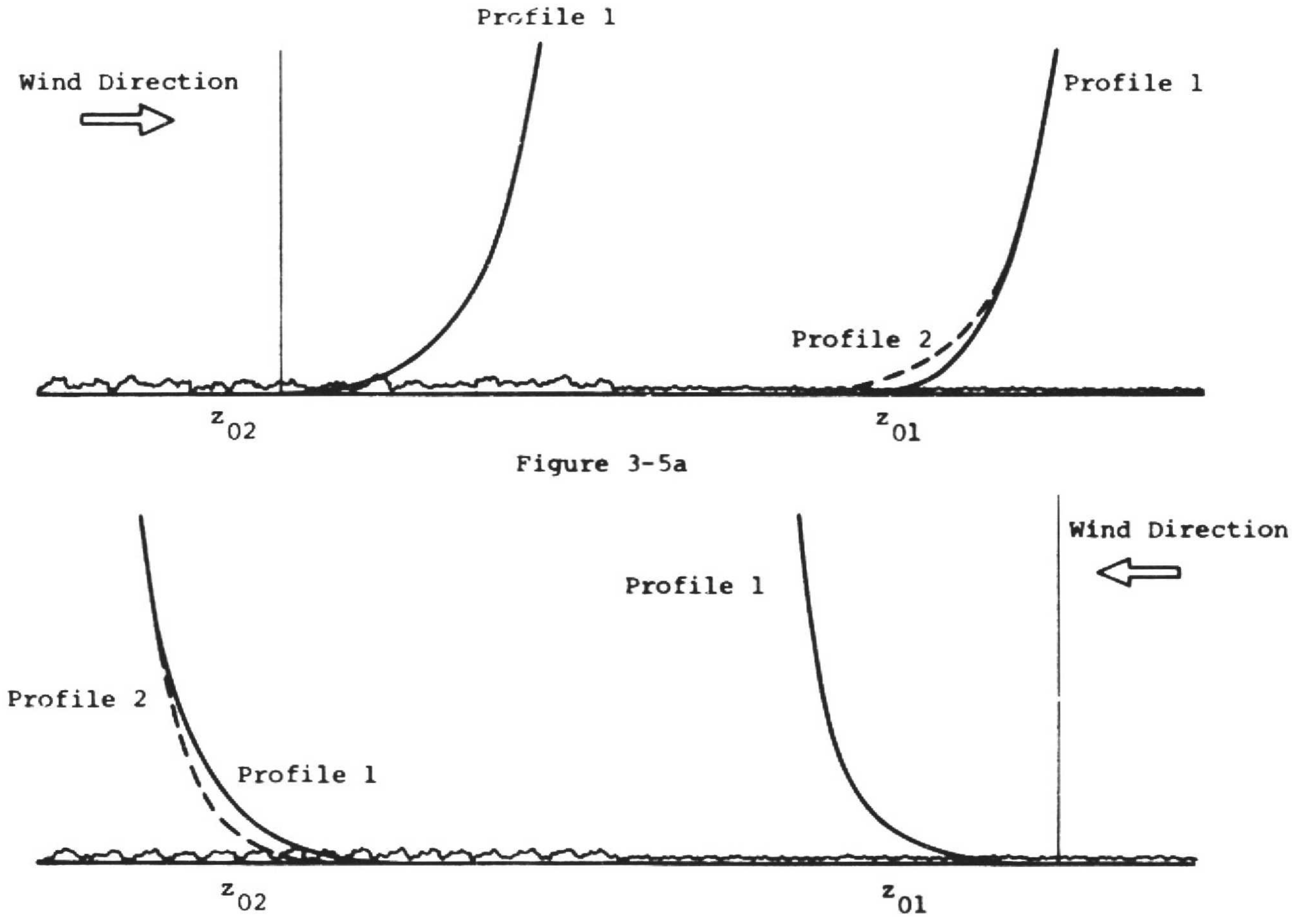

Figure 3-5b

Figure 3-5 Illustration of how the Horizontal Wind Profile Changes with Surface Roughness [7].

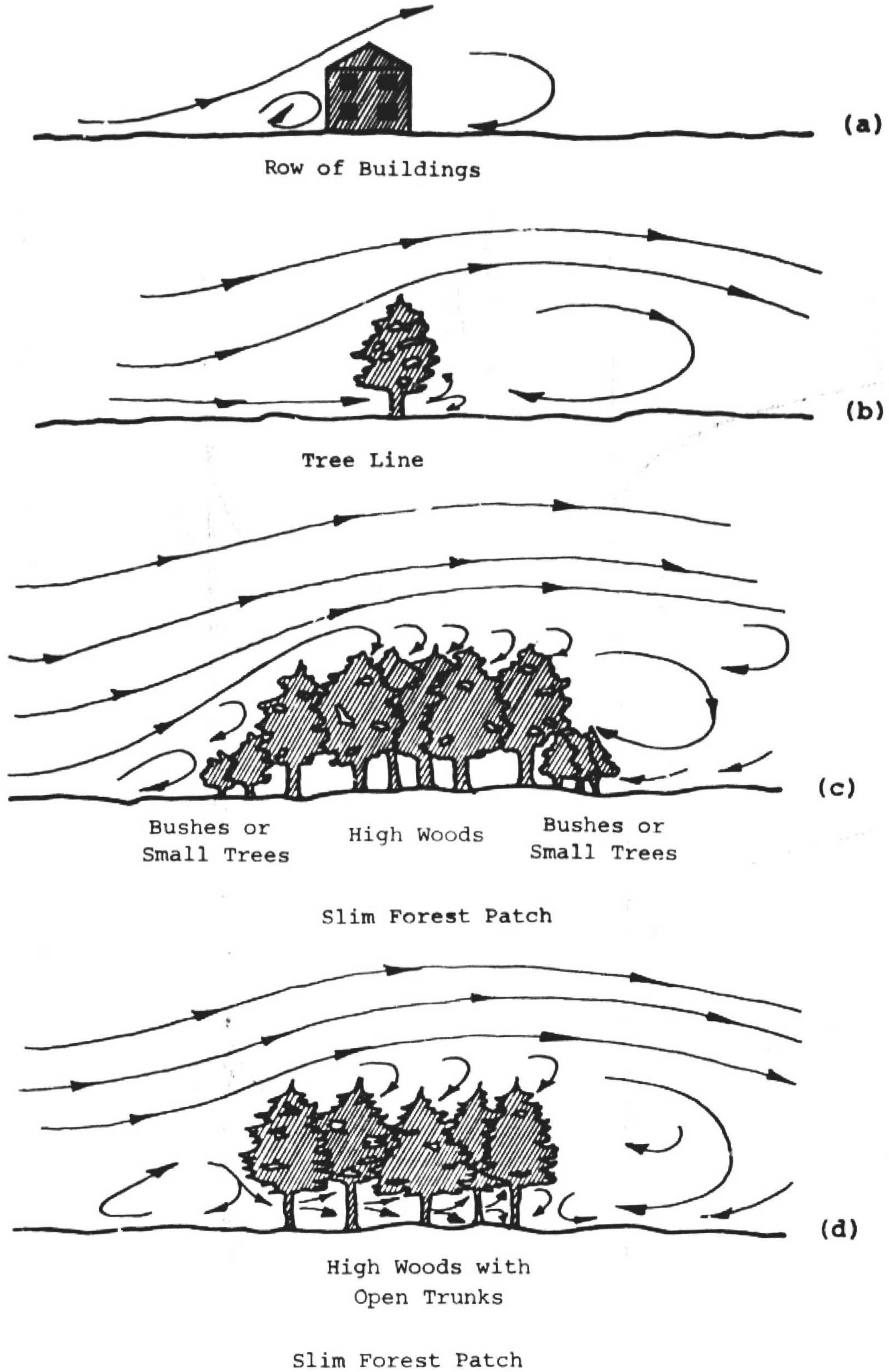

Figure 3-6 Flow Past an Obstacle such as a Row of Trees or Buildings [7].

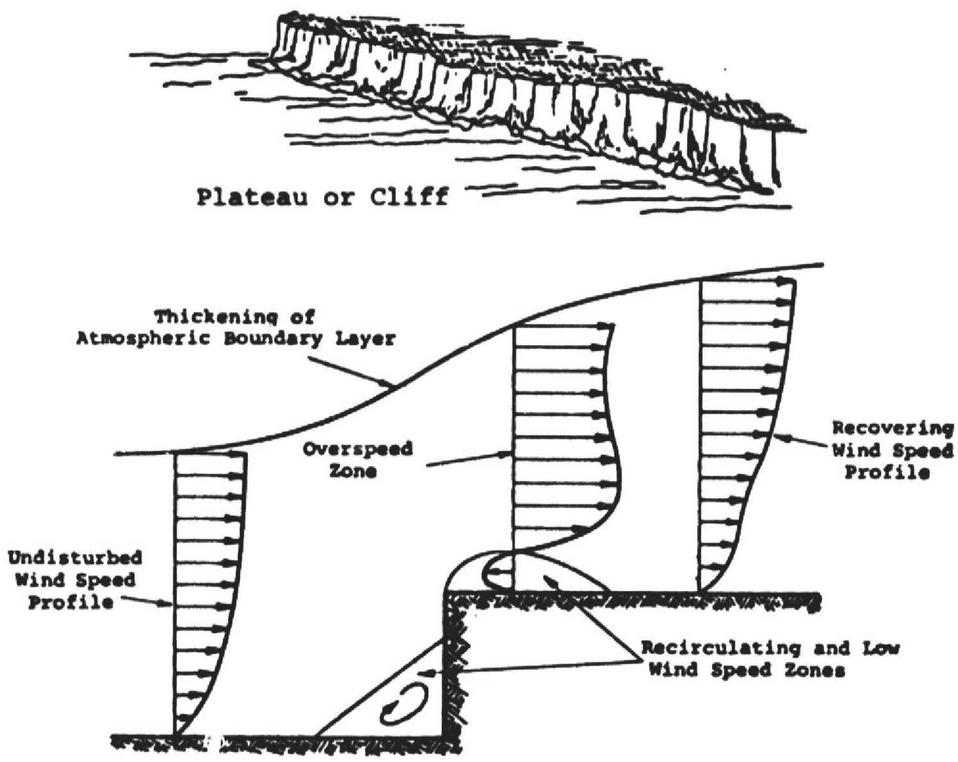

Figure 3-7 Flow over a Plateau or Cliff [7]

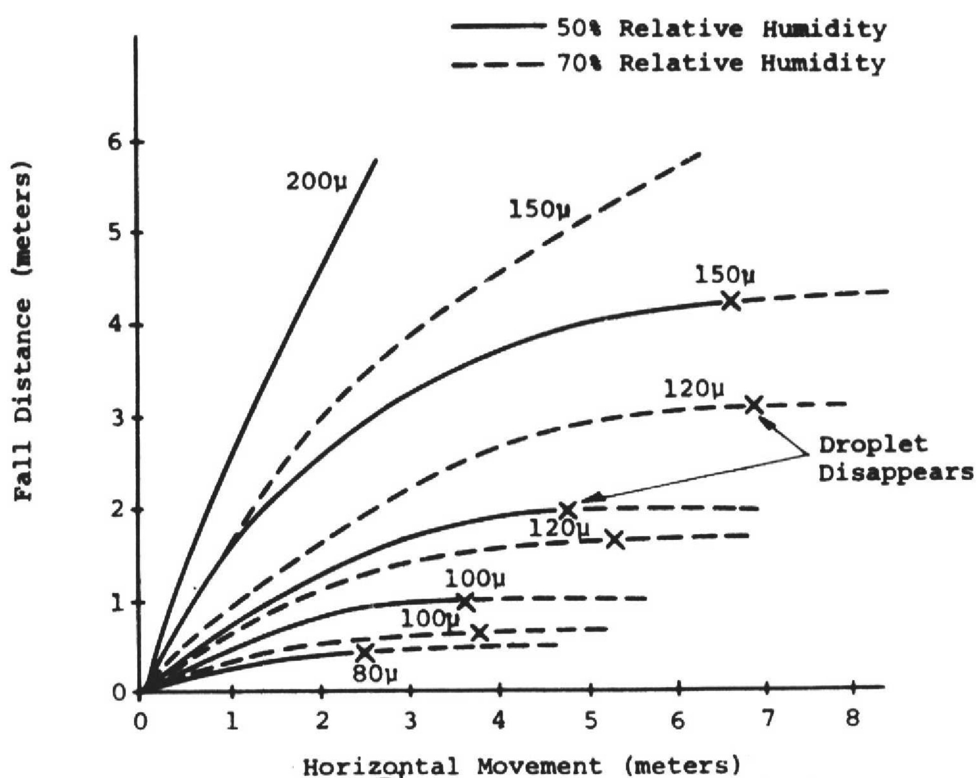

Figure 3-8 Effect of Relative Humidity on Spray Droplet Horizontal Movement. (Horizontal wind velocity 0.5 m s^{-1}) [8]

profile. As the horizontal wind increases, the drift distance also increases. Second, the drift of chemical sprays is inversely proportional to the vertical settling velocity which, in turn, is dependent on a number of factors--principally, droplet size. The droplet size is, in turn, dependent on a number of parameters among which the relative humidity and temperature play important roles. At higher temperatures and lower relative humidities, the droplet size decreases more rapidly due to evaporation and therefore its settling velocity decreases, thus increasing the drift distance.

The development of fine droplet spraying techniques appeared some years back and is still advocated by workers in the field of aerial application of agricultural chemicals. Recently though, because of the widespread concern with drift, the industry has moved in the reverse direction. The EPA is currently registering chemicals with application rates as high as 5 gallons/acre, solely for the purpose of obtaining large drops to minimize drift. Fine droplet spraying, low volume or ultra low volume is very attractive from a number of standpoints--including low mission operating costs and excellent spray effectiveness in controlling pests. These reasons have created an urgent need for research into factors affecting droplet evaporation. The intensity of the evaporation depends on a number of meteorological parameters: the temperature of the air and liquid, the relative humidity of the air, the form of the evaporating surface, the wind speed, and the nature of the liquid. More information is needed, however, to adequately assess the quantitative effect of these parameters on the dispersion of aerial-chemical applications.

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4.0 REGULATIONS

In the past, regulations concerned with aerial application of chemicals have principally dealt with the safety of the aircraft pilot. Today, regulations are addressed to all aspects of the environment. The Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) as amended in 1975 delineate the present regulations, limitations, and tolerances for agricultural chemicals. Any new chemical put on the market must be approved by EPA, a process called registration. Any changes in the product after registration are also subject to EPA approval. Today the EPA is principally interested in four main aspects of chemical application:

- Does the chemical do what it claims?
- Is there an adverse effect on the environment?
- Is it being used consistent with label instructions?
- Is it a usefu.. product?

It is interesting to note that meteorological measurements are being discussed as possible requirements to assure compliance with EPA regulations. The following list of aerial spray applications have recently been discussed for possible inclusion in the regulations [1]: (1) a diagram of the area to be treated including flight paths and prevailing wind direction, (2) meteorological measurements of temperature gradient, wind profile, relative humidity, etc., (3) the type and amount of adjuvant, (4) nozzle type, size, position, orientation and distance from nozzle to target, (5) drop size distribution, (6) quantity of diluents and active ingredients per acre, (7) aircraft speed, (8) spray boom pressure, and (9) distance tc nearest body of water. These suggestions are being adopted on current chemical labels.

Tolerances and exemptions have been established by the Environmental Protection Agency in Title 40, Code of Federal Regulations, Part 180. A table illustrating a few of the established tolerance levels is presented in Table 4-1 [2].

TABLE 4-1

ESTABLISHED TOLERANCE LEVELS (1977) FOR SEVERAL HERBICIDES AND INSECTICIDES AS SET FORTH BY THE ENVIRONMENTAL PROTECTION AGENCY (EPA) IN TITLE 40, CODE OF FEDERAL REGULATIONS, PART 180 (The tolerances established for pesticide chemicals in this table apply to residues resulting from their application prior to harvest or slaughter.) [2]

Chemical	Crop	Tolerance (parts per million)
Toxaphene	Apples, beans, corn, etc. Barley, oats, rye, wheat Soybeans	7 5 2
2, 4-D (2, 4-Dichloro-phenoxyacetic acid)	Rangeland Grass hay Barley, oats, rye wheat Rice, blueberries	1000 300 0.5 0.1
DDT	Grapes, lettuce, tomatoes Soybeans Apples, strawberries	7 1.5 0.5
Paraquat	Range grass, alfalfa Apples, tomatoes, etc.	5 0.05 (negligible residue)
Dicamba	Grass hay, pasture Asparagus, grain Milk	40 3 0.05 (negligible residue)
Silvex	Raw agricultural products	0.05
2, 4-Dichlorophenyl, p-nitrophenyl-ether	Broccoli, Cabbage, Onions Eggs, meat by-products	0.75 0.05
Picloram (4-Amino, 3, 5, 6 trichloropico-linic acid)	Grasses, forage Barley, grain Milk	80 0.5 0.05
2-Chloro-1-(2, 4, 5 trichlorophenyl) vinyl dimethyl phosphate	Alfalfa, forage Apples, corn, pears Eggs	110 10 0.1

TABLE 4-1 (continued)

Chemical	Crop	Tolerance (parts per million)
Endrin (hexa-chloroepoxyocta-hydro-endo, endo-demethanon-aphthalene)	Sugar beets Tomatoes Potatoes	0 0 0
Malathion	Forage crops Apples, vegetables Milk	135 8 0.5
EPN	Apples, tomatoes, etc. Almonds, cottonseed Soybeans	3 0.5 0.05
Methyl Parathion	Alfalfa Apples, vegetables, etc. Soybeans	5 1 0.1
Trifluralin	Carrots Alfalfa hay Fruits and vegetables	1 0.2 0.05
Alachlor	Forage Beans and peas Milk, eggs, etc.	3 0.1 0.02
Carbofuran	Alfalfa Potatoes Milk	40 2 0.1

Each state, however, has the right to establish like tolerances or adopt new ones. For example, the State of California has adopted the following limitation on residues of pesticide chemicals: "No residue of a pesticide chemical in or on produce is justified or permitted unless a permissible tolerance has been established by the Director, or unless the Director has authorized an exemption from a tolerance. The following tolerance levels have been established for DDT and Toxaphene: (a) The tolerance for DDT in or on produce sold for feeding livestock, including dairy animals, is 0.5 parts per million; (b) the tolerance for toxaphene in or on produce sold for feeding livestock, including dairy animals is 2 parts per million. Further, the Director has found and determined that herbicidal preparations containing any of the following substances or compounds thereof, referred to in these regulations as 'restricted herbicides': (a) 2, 4-D, (b) 2, 4, 5-T, (c) MCPA, (d) 2 4-DP, (e) Silvex, (f) 2, 4-DB, (g) Picloram, (h) Aopanil, and (i) Dicamba are injurous to many plants and crops grown in various areas of the state." The State of California then defines "hazardous areas" where the use of the above restricted herbicides is likely to produce a risk of injury to susceptible crops.

The above brief review indicates that the regulations for fungicide, insecticide, and herbicide applications are fairly complicated and somewhat ambiguous. Aerial application of certain chemicals under some meteorological conditions will probably be incompatible with off-target limitation and tolerance regulations. The meteorological conditions and important parameters affecting the conditions should be investigated. Investigations have indicated that the differential temperature and horizontal wind profile are two of the most important parameters affecting drift.

References Cited

[1] Conversation and discussion at the 1977 winter meeting of the American Society of Agricultural Engineers (ASAE).

[2] Code of Federal Regulations, Title 40, Protection of Environment Parts 100-399, pp. 308-413, 1977.

5.0 NUMERICAL MODELS

5.1 Introduction

During the past 30 years, great progress has been made in the development of numerical models pertaining to spray cloud behavior. Research has been carried out in the areas of environmental pollution applications, biological warfare, and, more recently, insecticide and herbicide applications. The overall objective has been and continues to be a more useful alignment between theory and field experiment in the physical description of aerosol and droplet behavior. The acquisition and use of experimental data for mathematical models has proved mandatory in quantifying the transport and diffusion of aerosols and droplets. However, many previous models have not been able to incorporate sufficient, accurate meteorological data to adequately study particle diffusion in a turbulent wind field. The use of experimental information is also essential in the design of field trials and in the interpretation of mathematical prediction model results. Deposition of aerial sprays on insects or vegetation is the result of many different processes, many of which are not well understood. Recent environmental concerns about insecticide and herbicide aerial applications have greatly increased the need for turbulence schemes in atmospheric diffusion calculations.

Numerical modeling of pollution dispersion has taken two forms. The initial and most readily used approach is the Gaussian plume model [1,2]. The other approach is the solution of the full Navier-Stokes equation with the appropriate equations for energy, mass transfer, and chemical reactions included. The latter approach is very much in the state of the art development as far as introducing turbulence into the solutions is concerned. Turbulence is modeled by either a mixing length model, by a two-equation model which utilizes transport equations for turbulence kinetic energy and length scale, or a second order closure model which solves simultaneously six to eight additional transport equations for all second order turbulence correlations such as the

Reynolds stresses, the thermal diffusivity, and the species concentration diffusivity. These turbulence models are described by Frost, et al., [3]. Additionally, a very complete development of the second order closure model is given by Donaldson [4].

All turbulence modeling, whether utilizing the Gaussian plume model or the full system of equations, requires empirical inputs to define the influence of turbulence. In the Gaussian plume model, spreading parameters which are related to the stability of the atmospheric conditions and other meteorological parameters must be measured experimentally. These parameters are described in Subsection 5.2. For the multi-equation turbulence models, all equations representing transport of turbulence quantities contain third order correlations terms which are modeled by dimensional analysis and engineering logic. The constants of proportionality appearing in front of these various terms must be determined by comparing computed results against experimental data.

To date, only limited applications of these models to the diffusion of particles or droplets distributed by aircraft have been carried out in which are incorporated the airplane induced turbulence generated by the trailing vortices. In fact, an understanding of the influence the presence of particles in the flow has on the momentum, energy, species concentration, and turbulent diffusion is still a subject for basic research [5]. Particle motion in trailing vortices is, however, currently under investigation and good comparison of numerical results with wind tunnel data is reported [6].

The line source Gaussian model or the point source in a constant wind field plume model should serve as representative models of released sprays. The major difference is that plume models normally assume a heated pollutant which would over-predict drift. This observation, however, suggests the interesting possibility of coaling the spray to achieve a higher settling rate and less drift.

Section 5.2 describes the plume models and the empirical inputs required for numerical predictions while Section 5.3 briefly reviews the full Navier-Stokes equation models.

5.2 Gaussian Plume Models

Concentration patterns are controlled by atmospheric diffusion, a process that depends on the state of the atmospheric turbulence at any location in time, although, atmospheric turbulence is usually not measured, this does not eliminate the need for accurate turbulence measurements. In fact, it strengthens the necessity of obtaining such information. At times it is useful to be able to describe the boundary layer turbulence in terms of routine measurements of the mean values (averaged over a time period of the order of 30 minutes) of meteorological quantities and their vertical gradients, principally the average temperature, the horizontal wind, and the vertical gradients of wind and temperature. The theory of the relation between these quantities and the turbulence has been worked out in considerable detail for the lower part of the boundary layer, and the effort has been, by and large, quite successful. Detailed summaries are given in a recent workshop on micrometeorology [4] and in a review by Panofsky [7]. However, the relation between the quantities and atmospheric diffusion is much less well understood. Therefore, it has been necessary to develop empirically based, more or less qualitative, turbulence schemes in order to handle practical atmospheric diffusion problems. These schemes attempt to relate certain average properties of the planetary boundary layer (including wind speed, stability, insolation, surface roughness and heat flux) to atmospheric diffusion.

There are a number of plume dispersion models that are used in describing plume behavior. These models of behavior are employed in the development of both mathematical, numerical, and empirical models. All of the models are based upon atmospheric stability, i.e., neutral, stable, and combinations thereof.

Coning Dispersion Model

This model describes plume behavior when the atmosphere conditions are neutral with moderate wind speeds. The plume dispersion pattern is shown in Figure 5-1, along with temperature versus altitude.* The plume

*The dotted line refers to a neutral atmosphere while the solid line depicts the stability condition for the particular plume dispersion model shown.

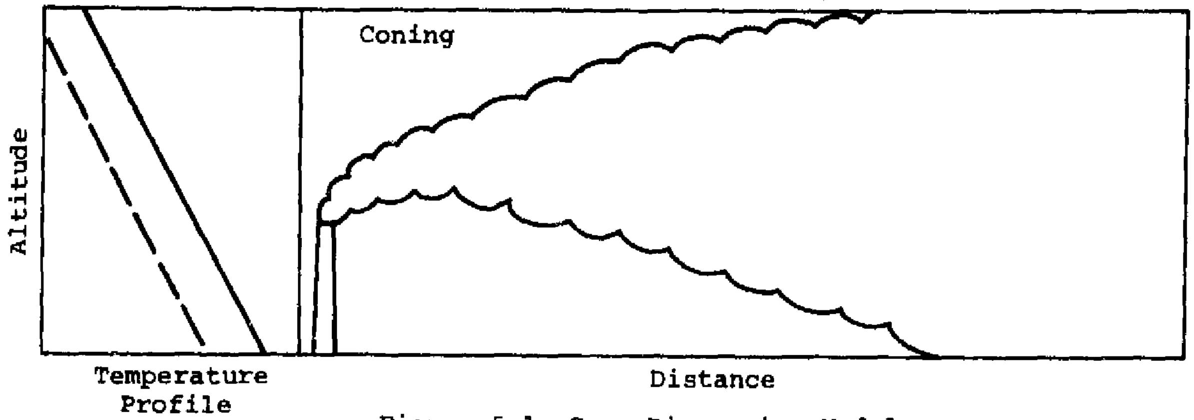

Figure 5-1 Cone Dispersion Model

can move both upward and downward in this situation. With high sources, the possibility of a concentrated plume reaching the ground is not usually great since the plume is well mixed with the surrounding neutral air.

A variation of behavior in the coning model is shown in Figure 5-2 and can occur when the plume impinges upon high terrain. In effect, the higher terrain gets in the way of the wind-driven plume and so the plume reaches the surface. Again, plume impactions at the surface are relatively low if the high terrain is a reasonable distance away.

One would expect that coning plumes would be commonly experienced in mountainous terrain, but this is not the case when the plume is released in a valley, well away from high terrain. In this situation, it lofts or rises as it moves downwind. This occurs because the air near the surface is heated by the sun as it passes over the valley floor. This heating causes the air to rise due to its lower density which sets up an unstable condition. The plume will tend to move upward if an upward force is present.

Fanning Dispersion Model

The plume fans, or spreads horizontally, at the effective source height. This mode[1], shown in Figure 5-3, occurs in a stable atmosphere as given by the corresponding stability diagram. This would be expected since under stable conditions, the plume tends to remain at the same level. The fanning model normally occurs almost daily because of the frequently observed stable conditions during late night and early morning hours.

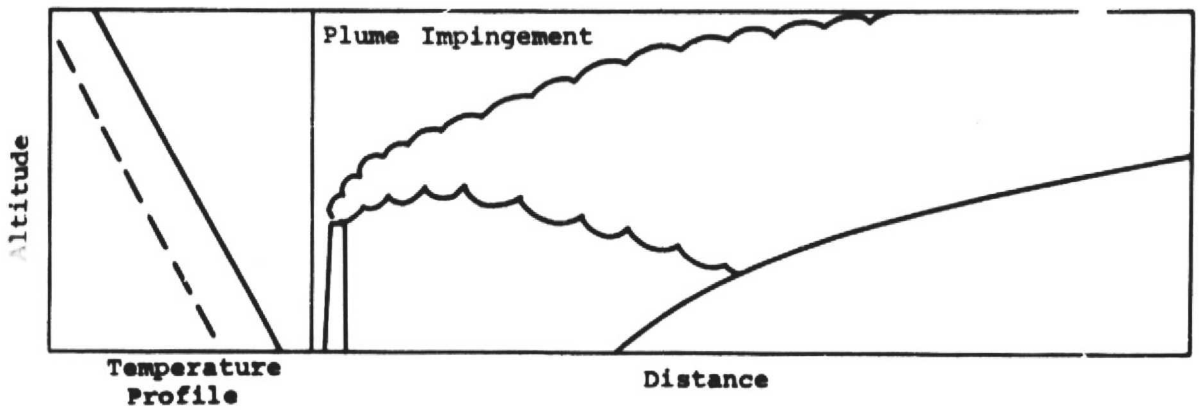

Figure 5-2 Cone Dispersion Model with Plume Reaching the Ground

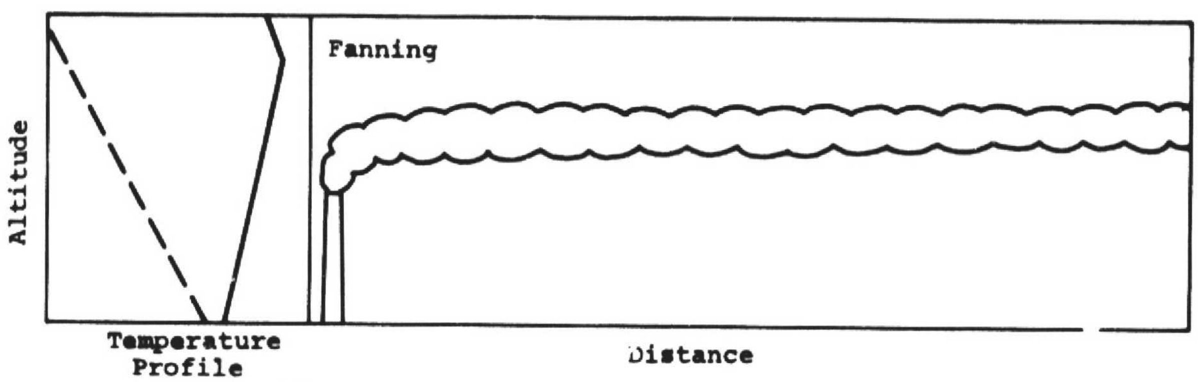

Figure 5-3 Fanning Dispersion Model

Inversion Breakup Model

This model of plume behavior, shown in Figure 5-4, along with the stability diagram occurs when the atmosphere is shifting from the stable to neutral or unstable. As indicated, the plume reaches the ground. High ground level concentrations are often observed during the breakup.

Inversion Trapping--Limited Mixing

In this model of behavior, the plume is trapped under an inversion with neutral air below. This condition, along with the appropriate stability diagram, is shown in Figure 5-5. Under light wind conditions, this can produce high level concentrations at the ground.

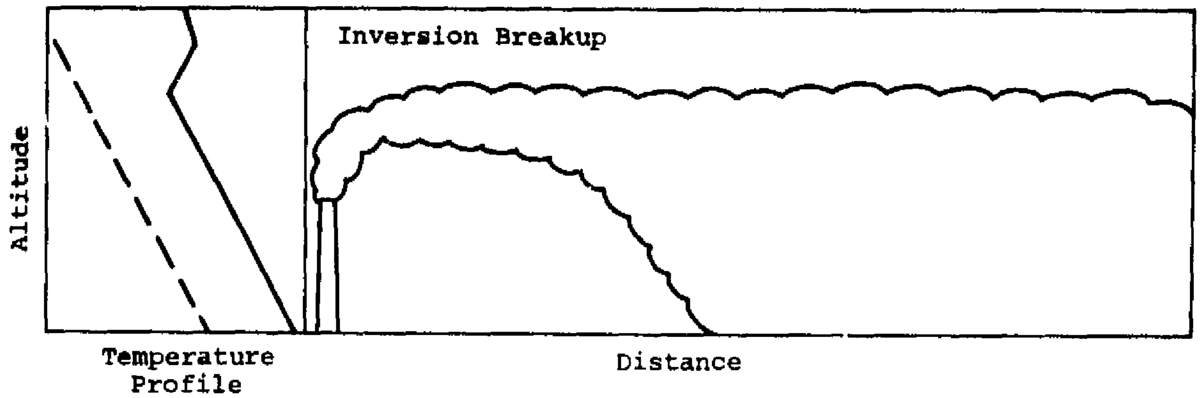

Figure 5-4 Inversion Breakup Model

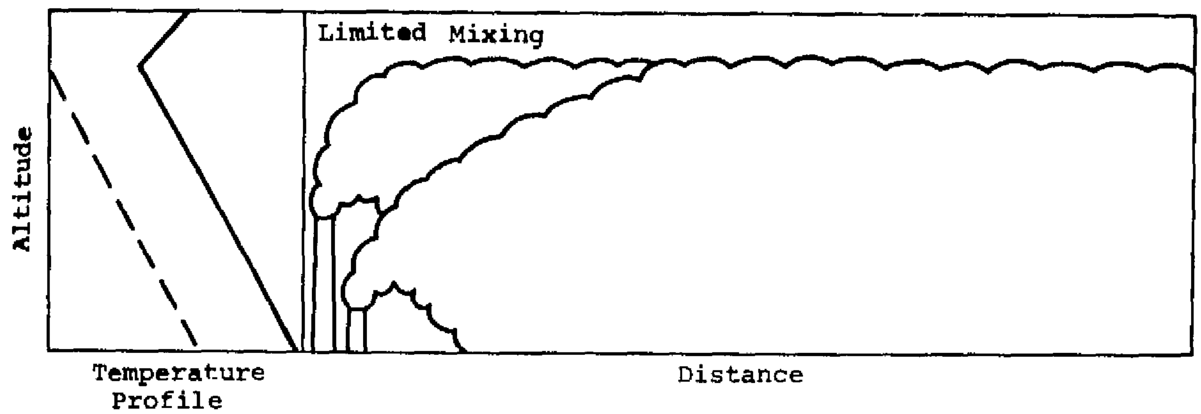

Figure 5-5 Inversion Trapping - Limited Mixing

The most widely used of several turbulence schemes is that proposed by Pasquill [8] for diffusion from low level, nonbuoyant sources over open country. Pasquill presents information on the lateral spreading, θ, and the vertical spreading, h, of diffusing plumes. He presents this data in the form of a graph for the latter and a table for the former as functions of six atmospheric stability classes designated A to F. These were arranged so that class A corresponds to extremely unstable conditions and class F to stable conditions. The quantities h and θ mark the 10 percent points of the plume concentration distribution relative to its mean center line value. The applicable stability category is chosen by reference to a table relating these to observed wind speed, cloud cover, and insolation conditions (Table 5-1).

TABLE 5-1

METEOROLOGICAL CONDITIONS DEFINING PASQUILL TURBULENCE TYPES [8]

A. Extremely unstable conditions
B. Moderately unstable conditions
C. Slightly unstable conditions
D. Neutral conditions*
E. Slightly stable conditions
F. Moderately stable conditions

Surface Wind Speed m/sec	Daytime Insolation			Nighttime Conditions	
	Strong	Moderate	Slight	Thin, Overcast or ≥ 4/8 Cloudiness†	≤ 3/8 Cloudiness
<2	A	A-B	B		
2	A-B	B	C	E	F
4	B	B-C	C	D	E
6	C	C-D	D	D	D
>6	C	D	D	D	D

*Applicable to heavy overcast day or night.

†The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon that is covered by clouds.

Gifford [9] converted the plume spreading data into families of curves of the standard deviations, σ_y and σ_z, of the plume concentration distribution (Figure 5-6). This was done partly because the standard deviation is a very commonly used statistic and partly to emphasize that the method could readily be used with the Gaussian plume formula. Pasquill's scheme has almost always been used and quoted in the form of these or similar graphs of σ_y and σ_z, which for this reason are frequently called the Pasquill-Gifford (PG) curves.

Briggs [1] proposed modifications of Pasquill's scheme to account for elevated and buoyant sources. The modifications are illustrated in Table 5-2. Smith [2] and Golder [10] proposed modifications to account for the theoretical boundary layer stability criteria. Modifications by Smith are shown in Table 5-3, while modifications by Golder are shown in Figure 5-7.

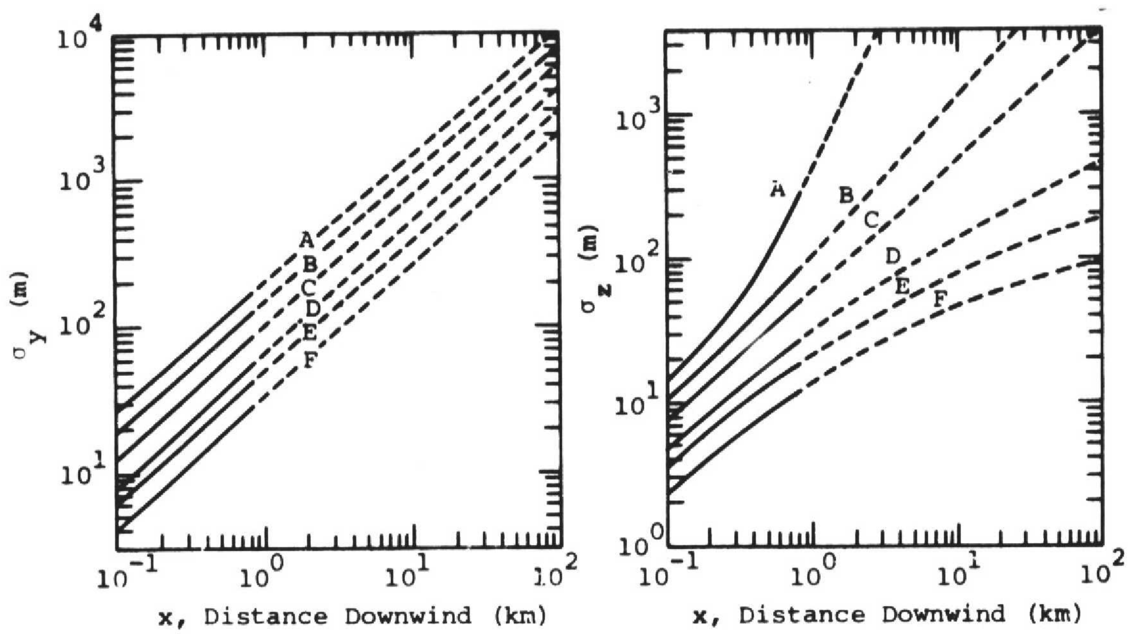

Figure 5-6 Curves of σ_y and σ_z for Pasquill's Turbulence Types Based on Pasquill [9]

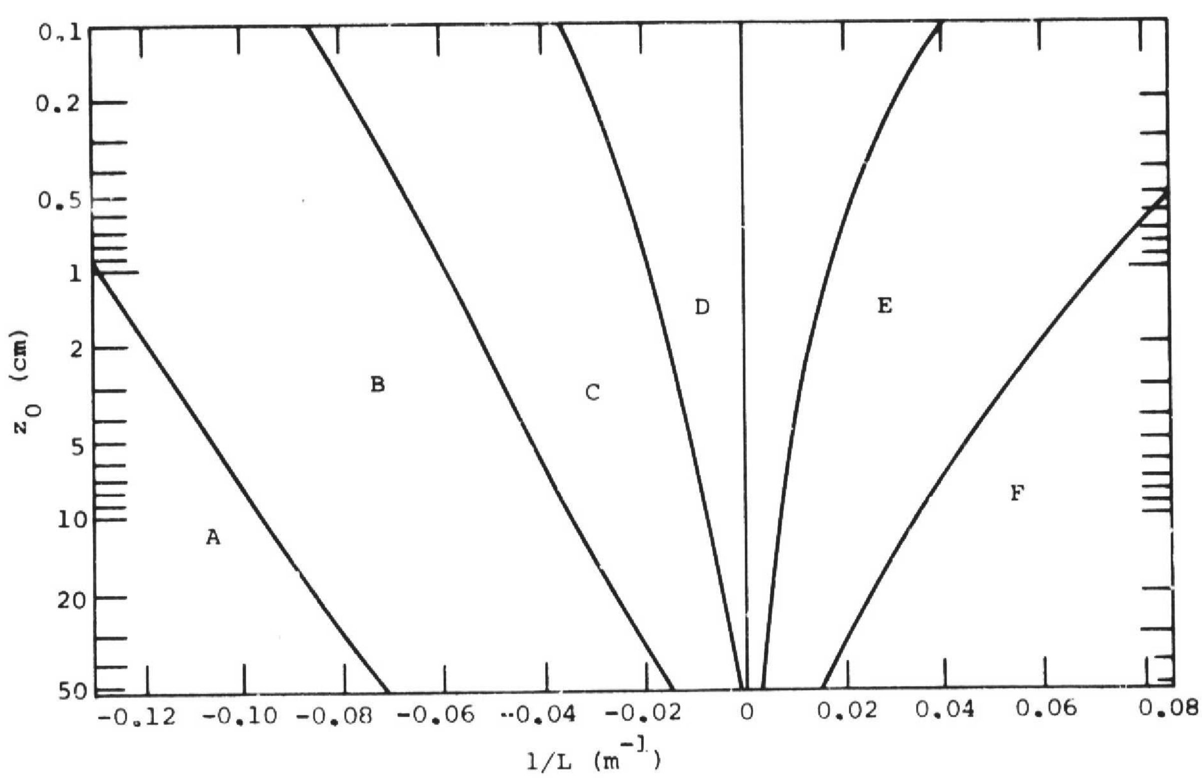

Figure 5-7 Curves by Golder Showing Pasquill's Turbulence Types as a Function of the Monin-Obukhov Stability Length and the Aerodynamic Roughness Length [10]

TABLE 5-2

FORMULAS RECOMMENDED BY BRIGGS FOR $\sigma_y(x)$ AND $\sigma_z(x)$; $10^2 < x < 10^4$ m, OPEN-COUNTRY CONDITIONS [1]

Pasquill Type	σ_y, m	σ_z, m
A	$0.22x(1 + 0.0001x)^{-1/2}$	$0.20x$
B	$0.16x(1 + 0.0001x)^{-1/2}$	$0.12x$
C	$0.11x(1 + 0.0001x)^{-1/2}$	$0.08x(1 + 0.0002x)^{-1/2}$
D	$0.08x(1 + 0.0001x)^{-1/2}$	$0.06x(1 + 0.0015x)^{-1/2}$
E	$0.06x(1 + 0.0001x)^{-1/2}$	$0.03x(1 + 0.0003x)^{-1}$
F	$0.04x(1 + 0.0001x)^{-1/2}$	$0.016x(1 + 0.0003x)^{-1}$

TABLE 5-3

RELATIONS BETWEEN PASQUILL TYPE, RICHARDSON NO. (Ri) AND L FOR FLOW OVER SHORT GRASS, z_o = 1 cm, ACCORDING TO PASQUILL AND SMITH [2]

Pasquill Type	Richardson No. (Ri) (at 2 m)	L, m
A	-1.0 - -0.7	-2 - -3
B	-0.5 - -0.4	-4 - -5
C	-0.17 - -0.13	-12 - -15
D	0	∞
E	0.03 - 0.05	35 - 75
F	0.05 - 0.11	8 - 35

There are various boundary layer flows that can be classified as exceptional in that they involve sources of turbulence (and hence diffusion) additional to the mechanical friction and thermal buoyancy that are the basic mechanism in Pasquill's original scheme. The turbulence categories have been extended in attempts to account for: (1) diffusion in near calm, very stable conditions; (2) diffusion over water; (3) diffusion near highways; (4) diffusion in irregular and rugged terrain; (5) diffusion over cities; (6) diffusion in the lee of flow obstacles (wakes). Diffusion over cities, highways and water are probably not applicable to agricultural spraying. Diffusion in near calm, very stable conditions; irregular and rugged terrain; and in the lee of flow obstacles will be briefly considered.

Atmospheric diffusion experiments reported by Sagendorf [11] suggests that under near calm, very stable conditions a plume is subject to a good deal of irregular horizontal meander or swinging. A review of several sets of diffusion data for light wind, stable conditions by Van der Hoven [12] indicates that the effective standard deviation values can correspond to anything between categories A and F. This supports Pasquill's original assertion that diffusion under these conditions will be very irregular and indefinite. In dealing with these conditions at any site, it will clearly be necessary as a minimum to have measurements or estimates of the azimuth standard deviation [13], as well as the usual quantities required to define the turbulence type. The turbulence produced by the aircraft itself will also be needed.

The diffusion in the lee of flow obstacles will most likely occur in agricultural applications where buildings and other obstacles are upwind from the field being treated. A wake (a region of low speed flow that extends downwind from a flow obstacle) is created in the downwind region from the obstacle. Within the wake the flow is turbulent, having properties at first strongly conditioned by the size and shape of the obstacle. The lower wind speed in the wake creates shear at the boundary, and the resulting fine-scale turbulence entrains air from the ambient atmospheric flow into the wake, gradually expanding it, reducing the velocity deficit, and ultimately dissipating the wake. Thus, dilution downwind of a source is strongly influenced by a nearby obstacle, whereas farther downwind it becomes dominated by atmospheric diffusion in the ordinary sense. More work needs to be done with various building shapes and arrays to adequately define downwind distances and the end of the wake region where ambient diffusion begins to dominate the flow. Until this work is done, it should be realized that results as presented by Bowne [14] may somewhat underpredict concentration values at large downwind distances in well-developed wake plumes. On the other hand, at small distances under stable conditions, when the wake is fully developed, the meandering effect results in lower concentration values than predicted.

As previously mentioned, Pasquill's scheme is designed only to account for mechanically and thermally generated boundary layer turbulence. Flows in rugged terrain have irregular, often turbulent, features that originate otherwise than with boundary layer turbulence and heat transfer, i.e., drainage winds, vortices shed from terrain obstacles, channeling effects, and flow separations of various kinds. None of these features were contemplated in the original scheme, and, consequently, departures from theory under such conditions can and do occur. Start, Dickson and Hicks [15] reported results of a series of diffusion measurements conducted in a deep, steep-walled canyon system in southern Utah. They found that diffusion rates are systematically greater within these canyon walls, implying departures from the usual Pasquill categories. Normally, application of chemicals in steep-walled canyons would not be practiced, but the study does indicate how diffusion is influenced by topographical features. Less severe, but similar features might occur in areas of confined farming. These departures resulted in lower concentrations, compared with those calculated from the usual Pasquill-Gifford curves. The differences range from a factor of 1.4 in category B (Table 5-1), moderately unstable conditions, to 4 in weak lapse to near neutral conditions, to 15 in category F, moderately stable conditions.

The authors state that most of the phenomenon mentioned earlier, i.e., greatly enhanced surface roughness, density flows, wake flows, and channeling effects were probably operating. Start, et al., [15] believe that their results represent a fairly extreme example of the terrain effect on diffusion categories and speculate that less rugged terrain, such as irregular farmland, should lead to departures intermediate between these results and the open-country values. More experimental work is clearly needed. From the examples given and the exceptional cases considered, more research and, in particular, more careful experimental studies are needed to resolve several of the important problem areas.

As previously indicated, much success has been gained using the classical diffusion equation, but as frequently pointed out, Sutton [16] and Csanady [17], uncritical use of the diffusion equation can lead to erroneous conclusions, especially for the distribution near the source. The concept was broadened by Cramer, et al., [18]. Generalized concentration dosage prediction models were first used by Milly [19]. He pointed out the necessity for separating the effect of the source factors (aircraft, etc.), meteorological factors, and site factors in the analysis and generalization of field test data. Bache and Sayer [20] have developed a simple model representing deposition from a sedimenting cloud diffusing about its center of gravity. The model was compared with tracer distributions obtained from line sources released in the lowest 15 m of the earth's atmosphere. Two of these models will be examined in somewhat more detail.

Cramer, et al., [18] have developed models which are intended to be universally applicable by suitable selection of source and meteorological input parameter values to all dissemination systems, to all environmental regimes, and to all requirements. These requirements typically include the design of field tests, assessment of the results of field measurements, extrapolation of these results to field operations, development of dissemination systems, and hazardous safety analysis, among others. The basic generalized model format is a mass continuity equation that in principle provides a complete description of the trajectory and properties of an aerosol or heavy particulate cloud from the time of cloud stabilization (approximate equilibrium with ambient conditions immediately following dispersal) until the cloud has passed beyond the maximum downwind travel distance of interest. The model equations are similar in form to the Gaussian diffusion model formulas first developed by Sutton [16] (and later extended by Pasquill [8] and others). A Cartesian coordinate system is employed with the origin placed at ground level directly below the source.

Of course, it should be recognized that the generalized model formulas are inherently interim or state-of-the-art expressions reflecting the best available knowledge. Because of inadequacies in existing experimental measurements, the amount of rigorous model validation that has been possible to date is disappointingly small. However, recent work in model validation has demonstrated that the overall conceptual framework is sound and that the accuracy of model predictions is limited principally by the accuracy and adequacy of the source and meteorological inputs. The model was developed principally for use in open terrain and must be modified before it can be used to predict concentrations under different conditions.

In the generalized concentration model for aerial spray releases, the concentration of airborne spray material downwind of the point of cloud stabilization is given by the product of five concentration terms: (1) peak, (2) along wind, (3) edge effects, (4) vertical, and (5) depletion. Auxiliary model formulas used to define the standard deviations of the concentration distribution (σ_x, σ_y, σ_z), which contain the turbulent intensities, diffusion coefficients, wind velocity, and other meteorological parameters, are also presented. Indications are that a number of factors are involved in droplet transport and diffusion, but it seems evident that the most important factor with respect to transport is meteorological effects. One thing seems evident: every parameter which is important in the diffusion process seems to be interconnected with almost every other parameter. It would be highly desirable to conduct experiments in such a way that 100 percent of the mass could be accounted for; this would produce the most meaningful results.

Bache and Sayer [20] have also developed a model of aerial dispersion. It is a simple model representing deposition from a sedimenting cloud diffusing about its center of gravity. Comparisons were made with tracer distributions obtained from aerial released line sources in the lowest 15 m of the atmosphere. It was shown that for clouds of light particles the distribution was characterized by the position of maximum concentration, which occurs at a distance proportional to the release height and inversely proportional to the turbulent intensities. Ground deposition estimates were provided from line sources oriented parallel to and perpendicular to the wind direction. They indicate that, on the basis of Csanady's [17] model and experimental data, the growth rate of an instantaneous line source in the lowest 15 m of the atmosphere was fairly well represented by the relationship $\sigma = 0.77IX$, where I is the turbulence intensity over the range $0 < \sigma \leq 3H$, and where H is the initial height of the cloud. They also state that it seems reasonable to suppose that the average dispersion from a line of spray will respond to turbulence in much the same way as a plume emitted from a continuous point source. To provide the initial conditions of the spray cloud, the use of line source models may be improved or possibly replaced by the use of aircraft wake models.

Necessary Input--Meteorological Parameters

There are numerous meteorological parameters that need to be included in a diffusion model of agricultural aerial spraying. The terms that should be included in a generalized model must specify the direction and rate of downwind cloud travel, the along wind, the crosswind, wind shear and the vertical cloud dimensions as functions of travel time and distance. The model should also include the distribution of material within the cloud as a function of time and distance, and the losses of material through decay or removal by such agencies as hydrometeors, gravitational settling, and other surfaces. The model must also provide for the effects of (1) variations in the chemical and physical properties of the material contained in the stabilized cloud, (2) the mode of release and emission time, and (3) the meteorological terrain and plant canopy factors. The model must also provide for the turbulence effects resulting from the aircraft itself. It is evident from the above mentioned parameters that the amount of experimental data available for modeling is at best meager. Detailed and accurate experimental results are needed to validate and demonstrate the accuracy of model predictions.

5.3 Two-Equation and Second Order Closure Models

The major problem facing numerical modelling of turbulent flows is the so-called "closure problem." The expression "closure problem" simply implies that there are fewer equations than unknowns available to close the set of equations necessary to effect a solution to the turbulent flow. The early numerical models, therefore, assumed a mixing length which was algebraically prescribed and solved effectively the same governing equations for the mean flow as for laminar flow with an effective turbulent viscosity based on the length scale. The two-equation model, however, writes in addition to the equations for the mean properties, equations for the turbulent kinetic energy and turbulence length scale. The second order closure model utilizes equations for the second order turbulence correlations and attempts to model the third order correlations. There currently exist several models for the third order terms and much work is required to establish those which are most universal.

The second order quantities are the variances and fluxes of momentum heat and contaminants, such as $\overline{u'w'}$, $\overline{T'w'}$, and $\overline{C'w'}$. The second order methods as applied to atmospheric flows are developed by Donaldson [4]. Typical computed values of the flux profiles from Reference [4] are shown in Figure 5-8. The significant influence of the effect of the empirically determined value of α is illustrated. Field measurements of these profiles are scarce and only limited verification of the predicted results has been established. Figure 5-9 shows the spectral range of $\overline{u'T'}$ and $\overline{u'w'}$ from Reference [4]. The frequency range of these parameters extends to approximately, $n = 10$ hz for typical z and $\bar{u}$ values in agricultural applications. The response of cup anemometers is on the order of 0.1 hz and, therefore, hot-film anemometers or other techniques are required to measure meaningful turbulent momentum, heat, and concentration fluxes.

The second order closure models result generally in a collection of several nonlinear differential equations, first order in time, which can be solved with the appropriate boundary conditions by time stepping. That is, knowing the values of all the field variables at any instant, the equations can be used to predict the values at the next instant. Thus, extensive computer capacity and time must be committed to effect a solution to any given problem. On the other hand, these techniques were not developed initially for urban pollution prediction; rather they were developed for predictions of flows of technological importance. Their application to meteorological aspects of agricultural aviation will, however, enable the meteorological community to benefit from a decade of development.

Literature pertaining to turbulence transport abounds in all areas of fluid mechanics. It is, therefore, well beyond the scope of this

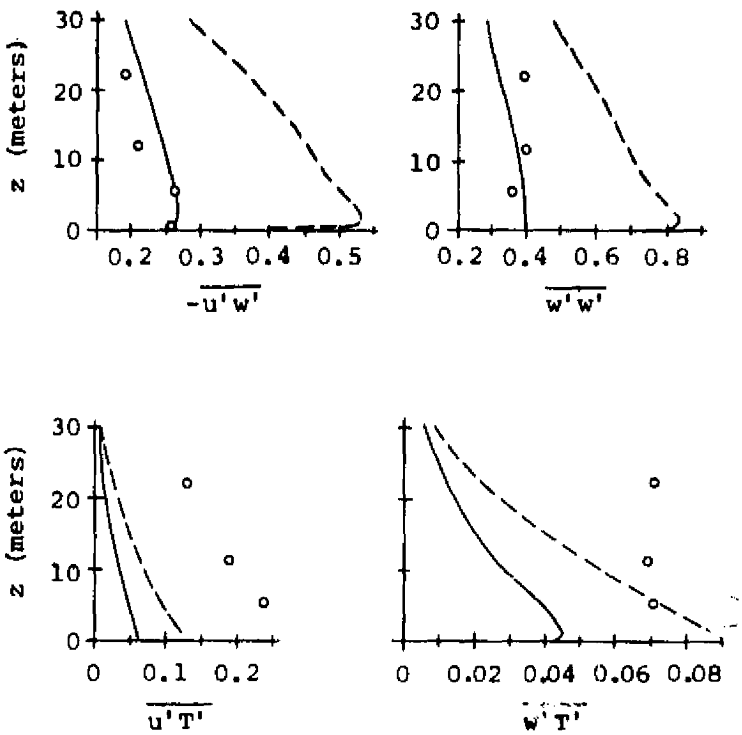

Figure 5-8 **Steady-state Distributions of the Velocity Correlations for the Profiles of Mean Velocity** and Temperature. (Near the surface, $\Lambda_1/z=\alpha=1.0$ for the **dashed curves** and for the solid curves $\alpha=0.7$. In both cases $\Lambda_{1max}=17$m) [4]

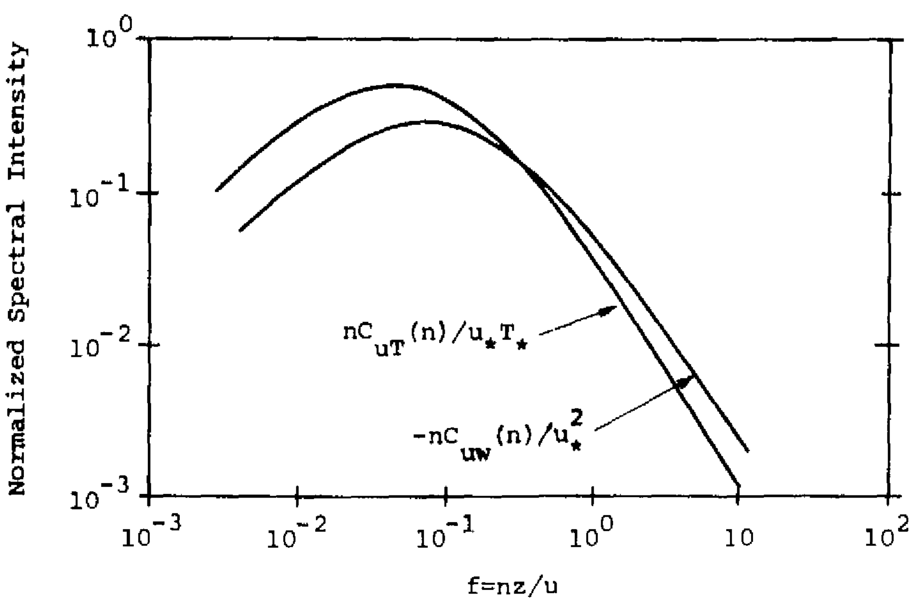

Figure 5-9 Near-neutral Spectra, Busch [4]

review to attempt to summarize all of the current research going on and how the applications of numerical modeling would pertain to research relative to agricultural aviation. Suffice it to say that models have been constructed, which, based on certain tensorial and dimensional analyses, have arrived at a set of closed equations whose validity tend to be obscured because of lack of comparison with well-documented experimental data. At the present time, there are more models for closure of the equation of motion at the second order closure level than there are principal investigators working on the problem. Lumley [21] recently summarized the basic experimental data necessary to establish a reliable air pollution model. It is clear from his work, that a great deal of meaningful and detailed experimental data in the atmospheric boundary layer is required in order to accurately test the models that are being developed. Some of the work in developing the model to its ultimate form can be done by considering laboratory flows in which different gases are mixed in classical free-jet and free-shear layer flow experiments. Some headway can also be made by considering the case of the compressible turbulent boundary layer. In the long run, however, it will be necessary to have extensive data from real atmospheric boundary layers if a high degree of confidence in the detailed prediction of any such numerical model is to be developed.

Currently, the second order closure model is being applied to solve the spreading of the agricultural chemicals in the vortex trailing the aircraft [6]. This model has shown very good prediction with wind tunnel experiments. The experimental parameters necessary to model the turbulent behavior of vortices appears to be reasonably well in hand; however, the authors are unaware as to whether the model will also predict the bursting phenomena which could have significant effect on spray dispersal. Moreover, the model has not been tested in the atmosphere when several additional parameters, including the energy equation, must be introduced into the system of equations to solve the complete problem. While this numerical modeling is continuing to be developed, it is necessary to simultaneously carry out field experiments with which numerical model predictions can be compared and from which the numerous experimental constants which appear in the two-equation and second order closure turbulence models can be verified or re-evaluated.

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6.0 SIGNIFICANT METEOROLOGICAL PARAMETERS

The transport of particles by atmospheric movement is the direct cause of agricultural chemical drift. The local meteorology can be a significant factor controlling the success or failure of a chemical spray operation. The diffusion transport and deposition characteristics of a wide range of particle sizes present in the drift of agricultural chemicals are very complex. The fundamental relationships for predicting drift concentrations are not yet fully established. Some of the major meteorological parameters that affect drift are: wind direction and speed, turbulence, air temperature, humidity, radiation, rain, and several micrometeorological factors related to the stability of the atmosphere.

6.1 Wind Direction

Wind direction is one of the most important and easily recognized parameters that can be used to prevent drift onto nearby areas. Timing the application during a period when the wind is coming from a particular field that is to be avoided will help to eliminate any damage caused by drifting chemicals. In a diversified farming area, however. susceptible crops are usually located somewhere downwind, and, thus, it is important to understand the meteorological parameters related to deposition at various distances.

Direction changes and recirculating flow regions due to flow around terrain features should also be considered and taken into account in regards to possible contamination to nearby susceptible crops. Terrain features have profound effects on wind characteristics. Two such features, valleys and plateaus or cliffs, will be briefly discussed at this time.

The wind is either enhanced or reduced upon encountering a valley. Several properties of valleys are important in this regard. The valley dimensions such as width, depth, length, side slopes, and the number of bends and constrictions are important. The orientation of the valley with respect to wind direction is also an important property to be considered.

When the wind is blowing parallel to a valley, there can be a funnelling effect. For example, if the valley narrows and the sides become steep, the wind is speeded up as it passes through the valley. A recirculation region, or eddy, may form if the wind is blowing at right angles to the valley. Differential heating during the day or cooling at night may intensify or reduce such a circulation.

The diurnal sequence of valley winds during light wind conditions is shown in Figure 6-1 [1]. White arrows illustrate upslope winds and black arrows illustrate mountain winds. Figure 6-1(a) is at sunrise when the valley is cold. Figure 6-1(b) represents mid-morning conditions. Figure 6-1(c) occurs near midday and early afternoon when the slope winds are diminishing. The valley is now warmer than the plains in the foreground of the figures. Figure 6-1(d) represents late afternoon conditions, the slope winds have ceased and the valley winds continue. Figure 6-1(e) illustrates conditions in the evening. Figure 6-1(f) represents the early night condition with well-developed downslope winds. This overall sequence is characteristic of the transition between valley and mountain winds. In the middle of the night, Figure 6-1(g), the valley is colder than the plains. Figure 6-1(h) represents the period from late night to early morning. It is evident from the above considerations one must be aware of wind in relation to terrain features such as valleys in order to help eliminate the possible drift of hazardous chemicals onto nearby susceptible crops. For example, a measurement of wind characteristics near the top of a valley may not be representative of wind characteristics on the valley floor. Assuming wind information from a particular location is the same at all locations could result in hazardous chemicals being deposited on nearby crops.

The other type of terrain feature to be briefly considered is the plateau or cliff. Experimental results [2] indicate that the airflow can separate or form an eddy at the top a windward-facing plateau, as well as, at the foot of the plateau. These separation areas are zones of turbulent air and may extend downwind several hundred meters. Also, the size of the separation zone may be quite unsteady in relation to the size and position of the surface feature, depending on roughness, wind and stability conditions. Figure 6-2 illustrates a typical wind flow pattern over a plateau.

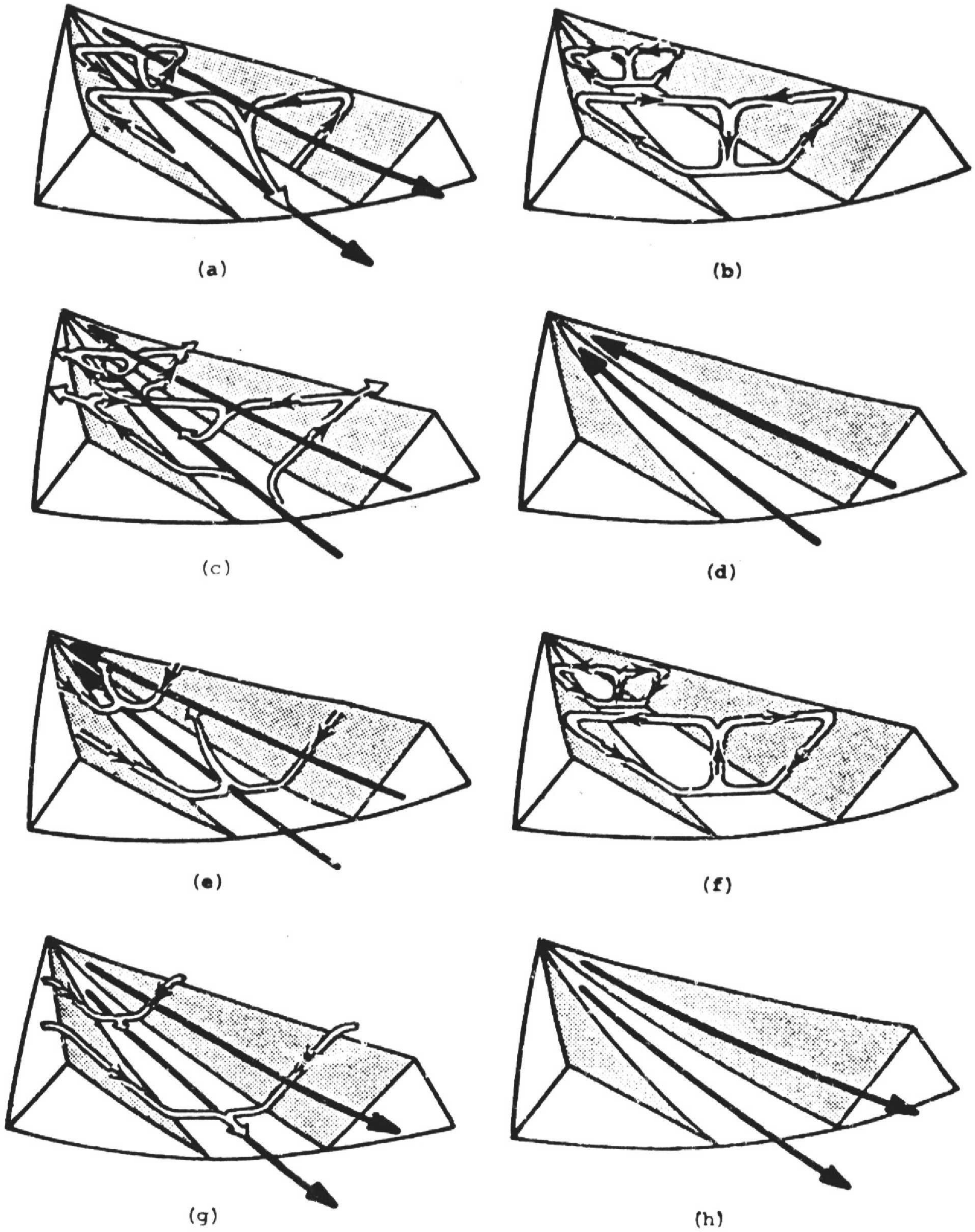

Figure 6-1 The Diurnal Sequence of Mountain and Valley Winds, [1]

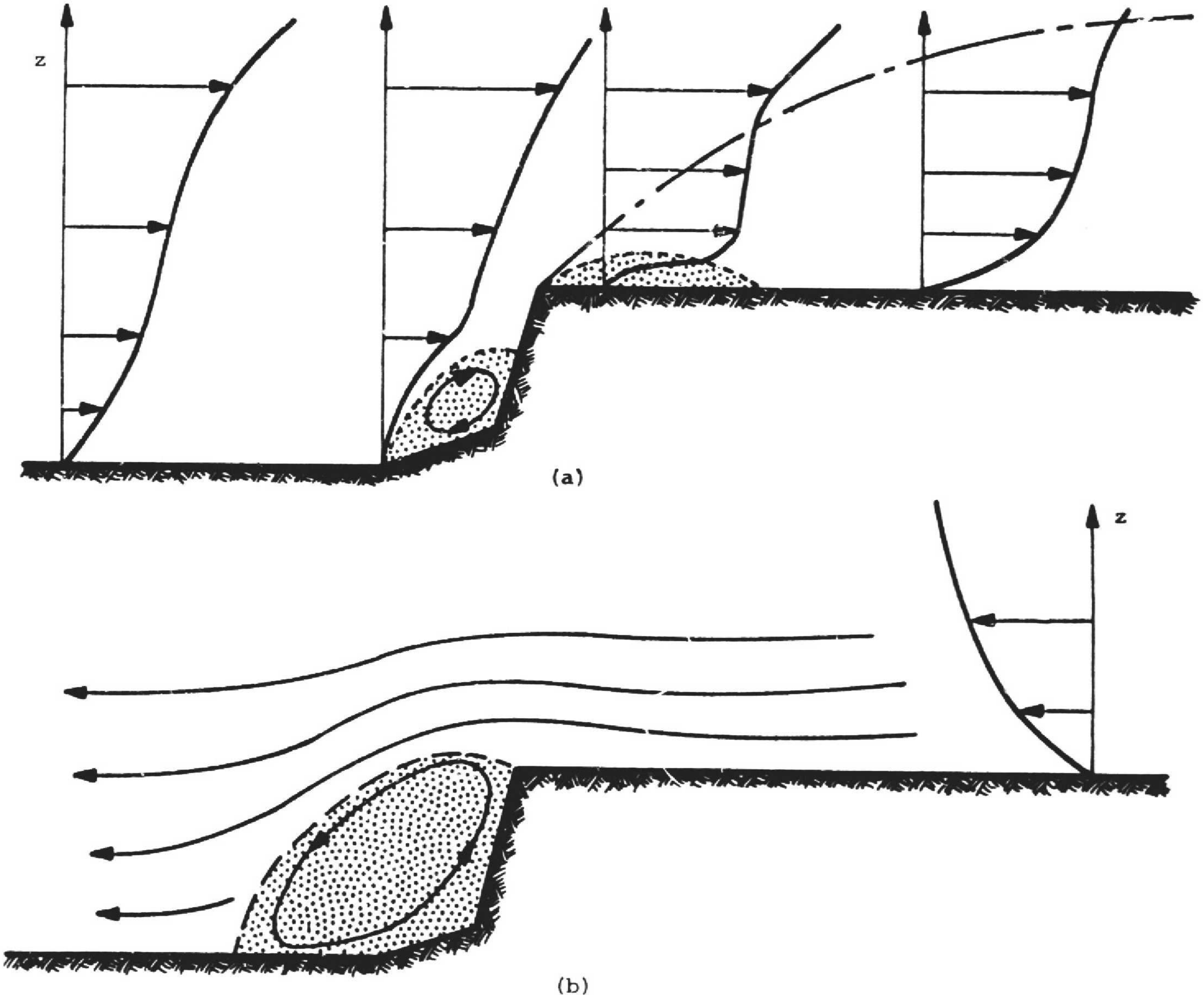

Figure 6-2 Flow over a Plateau: (a) Velocity Profiles for a Neutrally Stable Atmosphere; (b) Airflow in the Opposite Direction over a Steep Lee Slope. [2]

Although the exact transport mechanisms of aerosols and droplets subject to turbulent wind field conditions have not yet been fully established, the different wind characteristics encountered will have an effect on the transport of agricultural chemicals. Consideration of the wind characteristics near terrain features must be included in order to predict the potential drift of chemicals onto a nearby susceptible crop.

6.2 Wind Speed

Wind speed is of importance in determining transport distances and may provide an estimate of movement under stable conditions. Table 6-1 illustrates the theoretical horizontal transport for nonturbulent conditions with various size particles falling at terminal velocity for a vertical distance of 6 meters and displaced horizontally by an average wind velocity of 2.2 meters per second. The table is based on no evaporation and no turbulence as well as on a uniform wind velocity, whereas, in air movement near the surface boundary layer the velocity decreases with a decrease in height until it reaches zero at a height referred to as the surface roughness height, z_o. Wind velocity profiles vary with surface roughness, terrain features, and atmospheric stability. Thus, it is necessary to measure the wind velocity profile to provide specific information for calculating the transport of particles near the ground. In addition, the wind velocity gradient has a direct effect on the turbulence.

TABLE 6-1

DRIFT DISTANCE, NO EVAPORATION AND NO TURBULENCE

Drop Diameter (μm)	Horizontal Distance Particle Will Travel in a 2.2 Meters Per Second Wind While Falling 6 Meters, Assume Water Droplets
5	407.00 kilometers
10	4,500.00 meters
50	179.00 meters
100	52.50 meters
500	6.60 meters
1,000	3.35 meters

The evaporation rate of the particles is affected by air temperature and humidity. However, for nonaqueous solvents or active insecticides, the humidity does not affect the evaporation, and the air temperature is the principal meteorological factor affecting evaporation rates.

Chemical applications are usually not conducted during a rain storm; however, rain is one of the important mechanisms that removes or scavenges some of the fine agricultural aerosols that are carried into the atmosphere. It is known that rain drops will collide with the aerosol particles and collect them, thus removing the small particles in the air [3].

6.3 Turbulence

Turbulence is one of the major meteorological parameters affecting drift characteristics. Turbulence is a rather complex phenomenon consisting of horizontal and vertical eddies which can mix and, consequently, dilute the concentration of fine particles released in the atmosphere. Chemical application of insecticides and herbicides produce a wide spectrum of droplet sizes which are transported by a combination of forces produced by gravity, average wind velocity, and turbulence. For applications at close range to the target area, the turbulence created by the aircraft itself must be considered. The trailing vortices can either remain concentrated or burst. The influence of meteorology on this phenomenon is not currently understood. Nor is it understood how the residence time of the vortices over the crop area is affected by the vortex characteristics [4]. At a location some distance from the application, a kilometer or so, an increase in turbulence will generally decrease the concentration per unit volume of air, decrease the deposit on the ground and increase the vertical and horizontal size of the drift cloud.

Turbulence is related to the surface roughness, temperature gradient with height, and the wind velocity gradient with height. Turbulence near the ground is partially induced by the surface roughness characterized by a roughness length, z_o, which is dependent on the size and distance between the roughness elements. Vertical and horizontal eddies are mechanically produced as the airstream flows over and around the roughness elements. In addition, mechanical turbulence is induced by the gradient of wind velocity as it produces wind shear. The velocity gradient is generally greater near the ground, increases with wind speed, and is also affected by the surface roughness. The temperature gradient is important since it represents the energy available for producing or depressing eddies by buoyancy forces. Figure 6-3 illustrates a dry adiabatic temperature gradient which represents a neutral buoyancy condition. Any temperature lapse rate greater than this value is called superadiabatic and produces unstable conditions with eddies formed by convection currents produced as the less dense air parcel near the ground surface accelerates upwards to a position of equilibrium. Air temperature profiles that have less a lapse rate than the adiabatic lapse rate are commonly referred to as inversions. These inversions dampen vertical displacement and produce stable conditions; thus tending to hold the spray at an injected height and retard vertical or lateral spreading of the plume.

The temperature profiles near the ground change diurnally. Under hydrostatic conditions, which rarely occur for any length of time, the temperature profile can be represented by the equation $\partial T/\partial z = -g/c_p$ where g is the gravity and c_p is the specific heat at constant pressure. In the middle of the day superadiabatic or unstable conditions may exist near the ground because of high solar radiation. During the night, early morning, or late afternoon, a strong inversion or stable condition may exist. Figure 6-3 shows a typical summertime condition over an alfalfa field with a strong inversion present up to approximately 2,000 feet in the morning and a nearly normal adiabatic condition present in the afternoon. During the morning heating period, a mixed layer may exist near the ground with an inversion layer persisting aloft. A diagram illustrating the diurnal variation in lapse rate or temperature gradient is shown in Figure 6-4. The growth of the convective boundary layer as a function of time is shown in Figure 6-5 [5].

Smith, et al., [6] investigated the effect of various time periods on chemical application decisions using Goering's model [7]. The purpose of the study was to determine whether or not a particular time

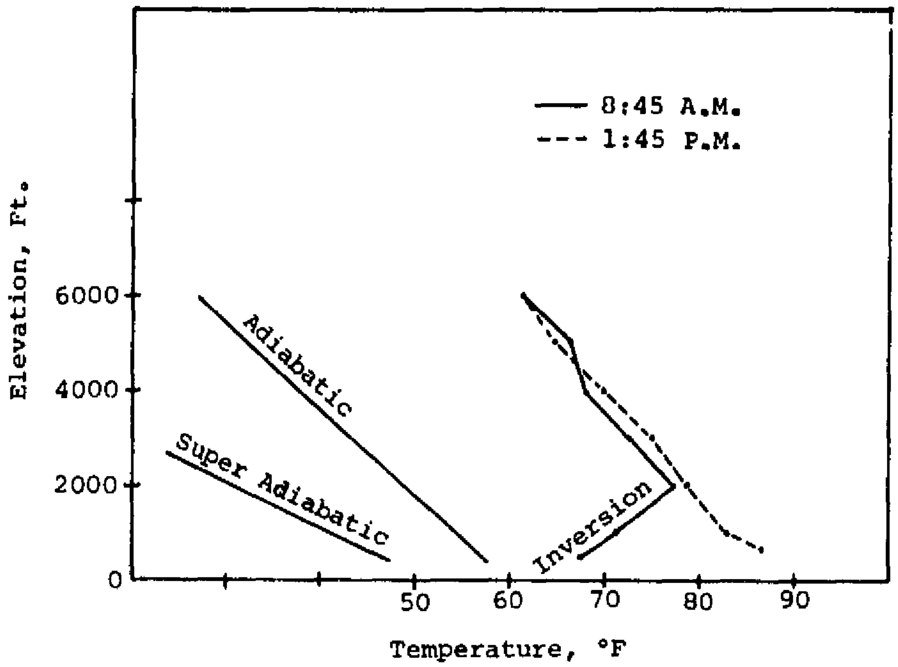

Figure 6-3 Temperature Profiles

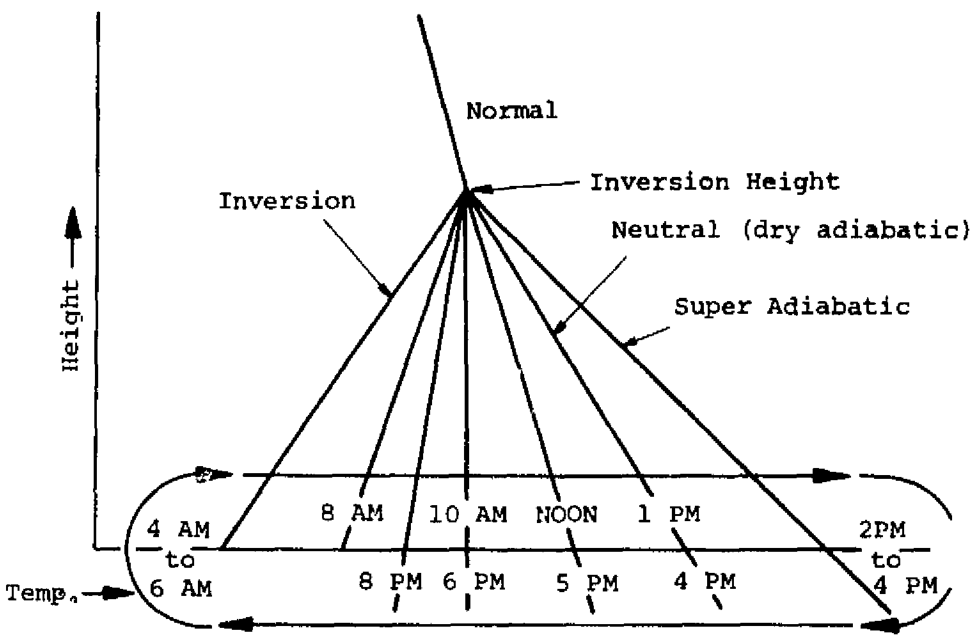

Figure 6-4 Diurnal Variation in Temperature Gradient

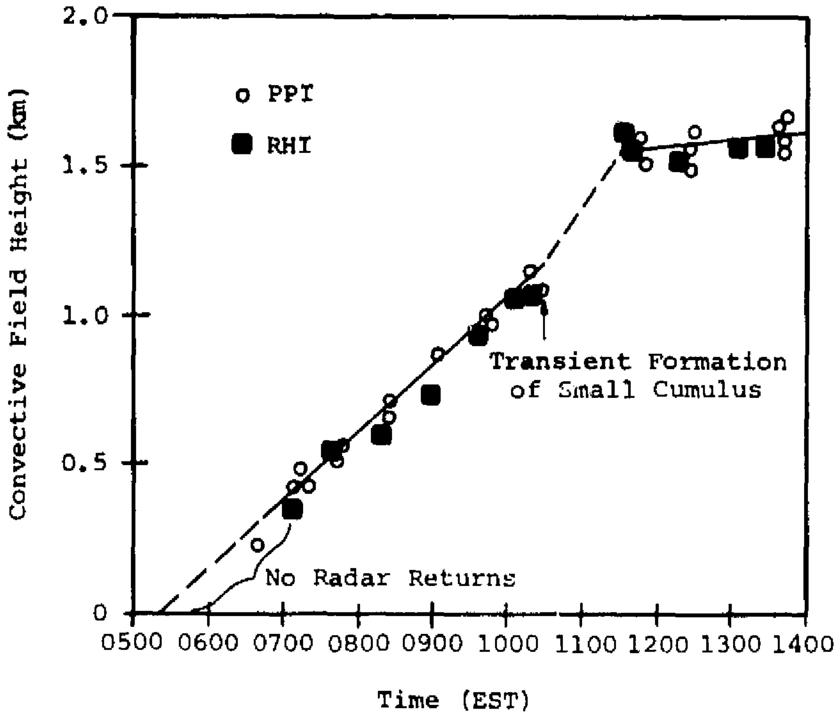

Figure 6-5 Some Radar Observations of the Growth of the Convective Boundary Layer. [5]

during the spraying season or specific time during the day exists when the probability of a successful application would be significantly greater than times normally used for application. The effect of various time periods on chemical application decisions were obtained using Goering's model [7] in conjunction with hourly weather data gathered over a period of several years to obtain the desired droplet size and distance predictions. Based on these droplet size and distance predictions, probabilistic calculations were then made for several time periods. Goering's mathematical molecular transport model is a simulation of spray droplet deceleration and evaporation. The variables included in the model are initial droplet size, height, nozzle pressure, velocity and direction of droplet, wind velocity at droplet height, air density, air viscosity, relative humidity, and dry-bulb temperature. The model uses the above mentioned variables to calculate droplet trajectories after the droplet leaves the spray nozzle. This model can also be used to study the behavior of spray droplets while holding some variables constant and varying the ones of interest. In the study by

Smith, et al., [6], all variables were held constant except for dry-bulb temperature, relative humdity, and wind velocity at a height of 2 feet. In order to make probabilistic spraying decisions, four final distances were selected as maximum acceptable drift distances (50, 100, 200, 400 ft.) and four minimum acceptable drop sizes were chosen (20, 30, 40, 50μm). Two separate analyses were made based on drift distance as shown in Figure 6-6 and droplet size as shown in Figure 6-7. These statistical tests show that for all four critical droplet sizes and distances, the probability of spraying at night (from 12 p.m. to 8 a.m.) was significantly better than spraying during the day, 99 times out of 100. Application of these results would be beneficial for ground operations but not totally for aerial operations, since FAA regulations will not permit applicators to fly at night. However, it appears that aerial applications might be improved by spraying during selected daylight hours. Information of this kind will also prove beneficial by enabling comparison of field test equipment and results under comparable atmospheric conditions. It should be noted that atmospheric turbulence as discussed by Yates, et al., [8] was not taken into account during the computation of these results.

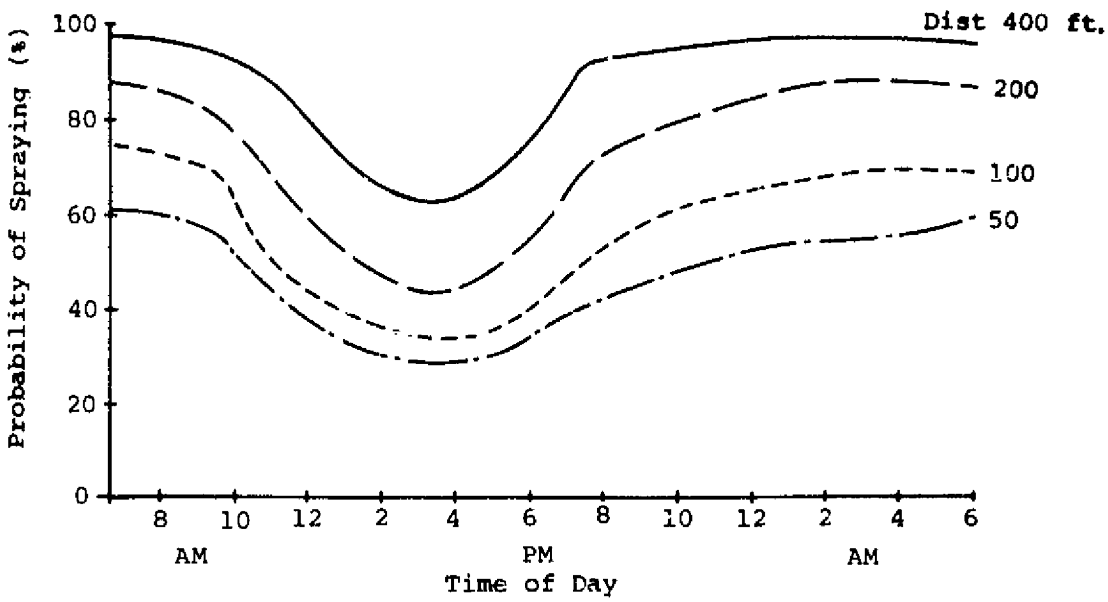

Figure 6-6 Probability of Spraying for Indicated Times of Day and Trajectory Distances [6]

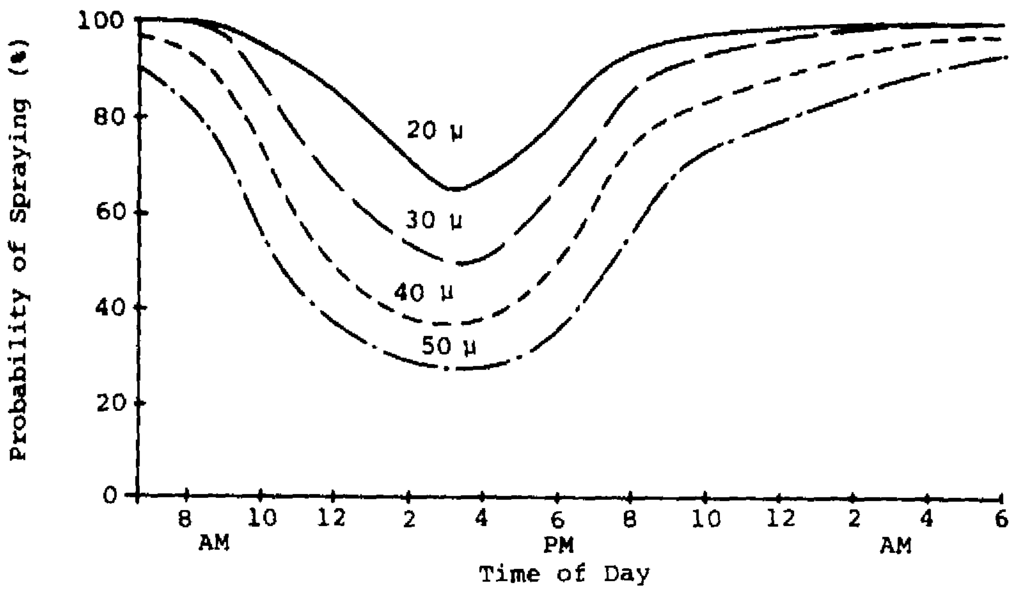

Figure 6-7 Probability of Spraying for Indicated Times of Day and Droplet Sizes [6]

In conducting experiments, a measure of atmospheric stability is required. The Richardson number, Ri, is frequently used to characterize stability conditions and is given by the following relationship:

$$Ri = \frac{\frac{g}{T}\left(\frac{\Delta T}{\Delta z} + \Gamma\right)}{\left(\frac{\Delta \bar{u}}{\Delta z}\right)^2}$$

where g is the gravitational acceleration, T is the absolute temperature, Γ is the adiabatic lapse rate, z is the height, and $\bar{u}$ is the average horizontal wind velocity. The Richardson number is a dimensionless parameter that relates the rate of buoyancy-produced turbulent energy to the rate of production of turbulent energy by wind shear. Under stable conditions, turbulence is suppressed, whereas with unstable conditions, turbulence is enhanced. It is, therefore, an indicator of the increase or suppression of turbulent motion in a variable height and density gradient. A large negative value indicates that convection predominates and is associated with strong vertical and lateral motion which would increase the rate of turbulent diffusion of the particles. Mechanical turbulence predominate as the Richardson number approaches zero. Large positive values represent conditions where the vertical or lateral motions are dampened; thus, minimizing plume spread in other than the mean wind direction. Since ΔT alone is not explicitly related to diffusion in the atmosphere, the use of the Richardson number, which accounts for both ΔT and vertical wind shear, may provide a more representative indicator. However, the Richardson number or parameter applies mainly to a particular ground surface and has limited value for comparing measurements over surfaces of varying roughness. Quantitative calculations of the Richardson number also require sophisticated instrumentation to accurately measure wind velocity and temperature gradients. Where such instruments are available, the Richardson number appears to be a good parameter or indicator for predicting dispersion of spray particles released from agricultural aircraft.

The stability ratio is a somewhat simplified index that has been satisfactorily correlated with drift deposit characteristics [9] and is given as follows:

$$\text{Stability Ratio} = \left(\frac{(T_2 - T_1)}{\bar{u}^2}\right) 10^5$$

where T is in degrees Celsius and $\bar{u}$ in cm s^{-1} and measured at a height equal distance from locations 2 and 1 on a logarithmic scale, position 1 is lower than position 2. The stability ratio is not affected as much by changes in surface roughness as the Richardson number. Also, the average wind velocity can be measured easier and more accurately than a velocity gradient.

Many researchers of aerial agricultural drift, including Threadgill and Smith [10], Smith, et al. [6], and Christensen, et al. [11] have found the stability ratio (S.R.) to be a useful indicator of the fallout of the spray cloud. The drift tests from previous investigations by Yates, et al., [8] have established four general categories of atmospheric stability:

Unstable	S.R.	-1.7 to -0.1
Neutral	S.R.	-0.1 to 0.1
Stable	S.R.	0.1 to 1.2
Very Stable	S.R.	1.2 to 4.9

With high wind velocities the S.R. will tend towards low values. Figure 6-8 illustrates the important effect of the stability ratio on the drift residue pattern. These two tests described in Table 6-2 directly compare drift residues under very stable atmospheric conditions with neutral atmospheric conditions [8]. At one-half mile downwind the residues were over 13 times greater during very stable conditions as compared to neutral conditions.

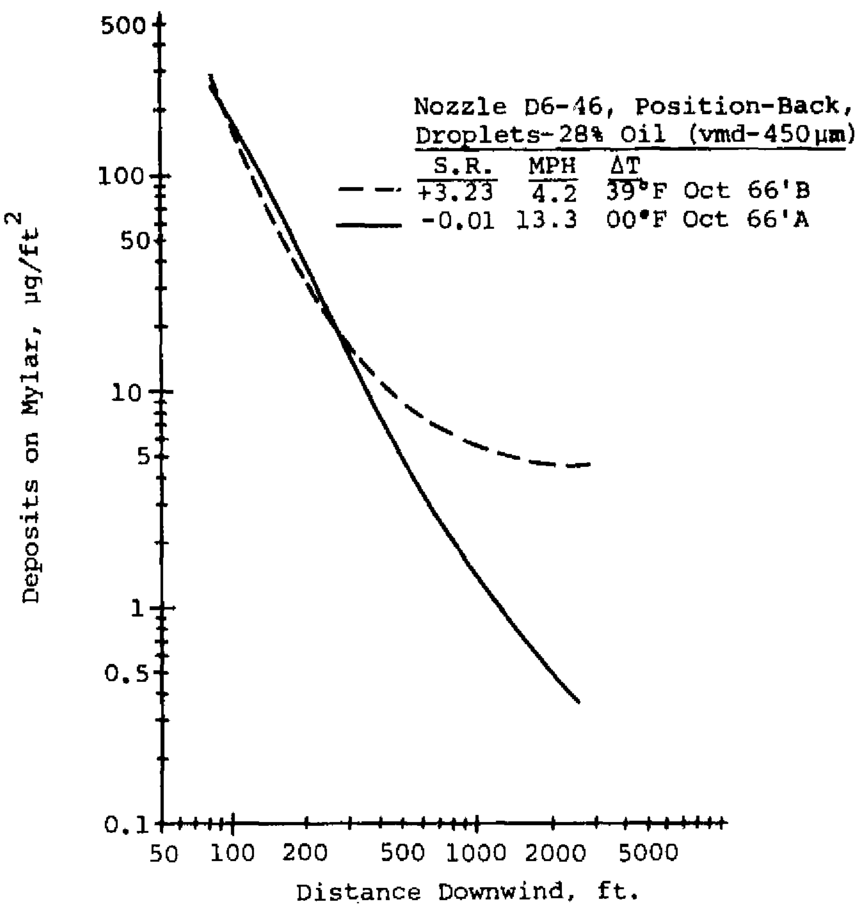

Figure 6-8 Effect of Stability on Drift Deposits [8]

TABLE 6-2

TEST CONDITIONS FOR OCTOBER, 1966 [8]

Test	Nozzles Type Orientation	Application Rate, gpa	Formulation Percent Oil Phase	Temp. at 8 ft. °F	Temp. Diff. $T_{32}-T_8$ °F	Wind Speed, mph			
						8 ft.	16 ft.	32 ft.	S.R.
Oct. '66, A	D6-46, back	5.3	2.8	69	-0.01	13.3	14.9	16.5	-0.01
Oct. '66, B	D6-46, back	6.7	2.8	66	3.85	4.2	5.8	7.7	3.23

From such data, Yates, et al., [8] concluded that to minimize drift residues, applicators should avoid spraying during very stable atmospheric conditions generally found during strong temperature inversions accompanied by low wind velocities. Moderate wind velocities generally produced nearly neutral conditions, and additionally reduced the residue concentration by dilution or spreading the material over a greater distance. Downwind concentrations of drift are rapidly reduced by temperature lapse (temperature decreasing with height), and moderate wind conditions; hence, these meteorological conditions are conducive to the least downwind contamination.

Skoog, et al., [12] investigated the value of the stability ratio as used to predict atmospheric stability when spray is dispersed from an aircraft at a height of 15.2 m. The S.R. was reasonably accurate in indicating upward and downward displacement of droplets, but not the extent of drift. Since the sign of the stability ratio depends entirely on the two temperatures, similar results could be obtained from the sign of the temperature differentials alone.

Statistical analysis was used by Threadgill, et al., [10] to determine the relative importance of several widely used parameters in drift studies. They were droplet size (XT), coefficient of variation of droplet size (CV)*, horizontal wind speed (V), vertical wind speed (W), and stability ratio (S.R.). An analysis of Figure 6-9 and the information in Table 6-3 shows that S.R. was the most important meteorological parameter for predicting drift [10]. As S.R. became less negative (i.e., the atmosphere became more stable and the tendency of droplets to remain aloft decreased) drift decreased rapidly. As XT increased, drift decreased to the extent that at a droplet size of approximately 140μm or greater (64 percent of the range of droplet sizes considered), no appreciable drift occurred. An increase in the upward direction of W resulted in a corresponding increase in drift.

The stability ratio has proven to be a helpful tool for condensing individual meteorological parameters into a single description of

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*CV is a measure of the variation in mean droplet size, expressed in percent.

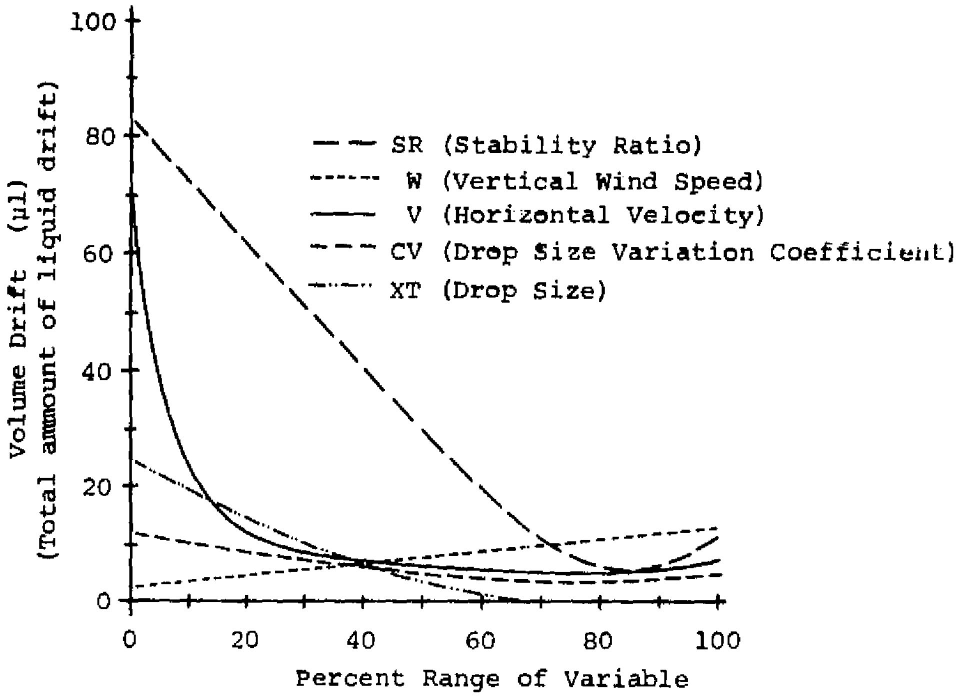

Figure 6-9 **Effect of Various Parameters on Drift as Predicted by a Regression Equation** [10]

TABLE 6-3

PARAMETER VALUES USED TO PREDICT DRIFT FROM THE REGRESSION MODEL [10]

Parameter	Normal	Range Minimum	Range Maximum
(Stability Ratio) SR	-1.83	-13.94	1.19
(Drop Size) XT, µm	94.13	17.00	202.00
(Vertical Wind Speed) W, mph	0.07	-0.06	0.22
(Horizontal Velocity) V, mph	6.30	1.39	13.05
(Drop Size Variation Coefficient) CV, percent	19.6	3.6	46.7

atmospheric conditions. However, the S.R. has its limitations and certainly cannot replace the close examination of other variables (wind velocity, wind direction, wind gradient, temperature gradient, relative humidity, etc.).

One other possible approach to characterizing the turbulence is to measure the three-dimensional variations of velocity with fast response hot-film anemometers, acoustic anemometers, or directional bivanes. Turbulence intensity can be defined as follows:

$$I_u = \frac{\sigma_u}{\bar{u}} ; \quad I_v = \frac{\sigma_v}{\bar{u}} ; \quad I_w = \frac{\sigma_w}{\bar{u}}$$

where σ is the standard deviation of the velocity variations of the component along the three axes, u is the component in the direction of average horizontal velocity, v is the crosswind component, and w is the vertical component. Thus, the above approach requires a rather sophisticated system to measure three variable signals simultaneously. A digital scheme can then be utilized to calculate the turbulence intensity. A somewhat simpler approach is to measure the standard deviation of the angular variation of two outputs from a bivane unit. It is important to recognize that the value of turbulence intensity is dependent on averaging time and that it requires experience to select the appropriate averaging period for the type and scale of diffusion under consideration. The standard deviation of wind direction relative to the vertical is also important in the diffusion of agricultural chemicals applied from aircraft. This azimuth (degrees) standard deviation of the wind direction relative to the vertical varies with height and wind speed. Neutral to moderately unstable conditions produce values between 5 and 10 degrees; extremely unstable conditions with light winds may approach 15 degrees; and, stable conditions generally result in a standard deviation of 2 to 5 degrees. Typical values of the standard deviation for conditions over agricultural fields are given by Christensen, et al., [11] and are shown in Figure 6-10.

6.4 Temperature Gradient

Previous discussion has indicated turbulence and temperature are interrelated. This section will discuss how typical temperature gradients are formed and their time of occurrence. A discussion of which meteorological conditions are optimum for some particular

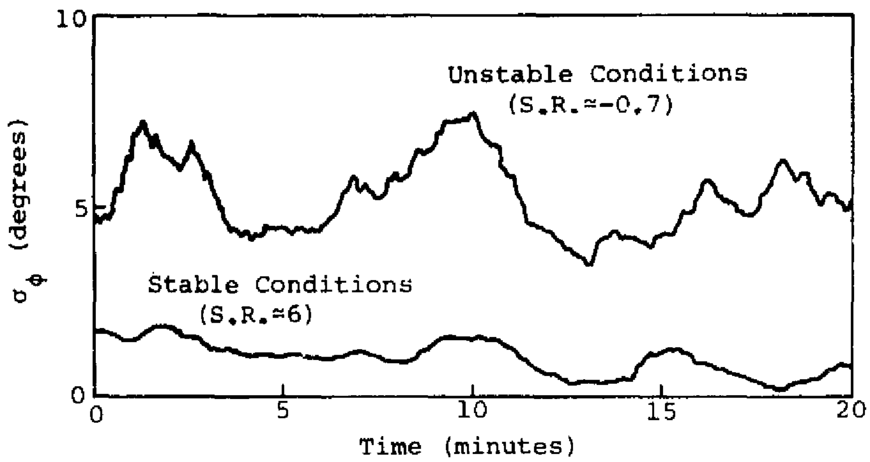

Figure 6-10 Typical Values of Standard Deviation for Conditions over Agricultural Fields [11]

applications will also be presented. Temperature inversions are produced by several means, and frequently more than one means may be the causing factor. The most common is radiation inversion caused by heat transfer due to radiation from the ground to a cool sky (when the sun is low or below the horizon); this heat loss cools the ground and the air close to it. Another important inversion cause is the influx over the land of a late afternoon sea breeze along coastal areas. This cold air pushes under the warm air and causes a temperature inversion condition. A third cause of temperature inversion conditions is subsidence, the phenomena by which air from a higher elevation is forced down into a lower level, such as a valley. This drop in elevation warms the air and places a warm layer of air over a valley to produce temperature inversion conditions.

Insolation however is the dominant effect and for this reason, the inversion and lapse conditions follow a diurnal pattern, with lapse and neutral adiabatic lapse rate conditions prevailing during the day when the sun's effect is strong, and the inversion conditions taking place when the sun is low during early morning or evening hours or at night (refer to Figure 6-4). During cloudy, overcast weather, the temperature gradient will vary from neutral to inversion conditions, depending on cloud density and the other gradient-affecting conditions mentioned.

When the air overhead is warmer (and this may occur at various levels) than that at the ground, any material released at the ground and transportable by air, such as droplets smaller than 50 microns, will be carried by the moving air along at ground level and will never diffuse upward. The air velocity under the inversion layer will control the mixing process in the area, and higher velocities will cause more rapid ground layer dispersion. It should be pointed out, however, that neutral stability conditions always exist at ground level. As z/L approaches zero, where L is the Monin-Obukhov stability length and z is the height above the surface, mechanical turbulence becomes predominate. When temperature gradients are increasingly cooler overhead above a warm ground, the spray can easily be diffused upward and is rapidly dispersed and diluted by wind.

The ideal or optimum meteorological conditions for aerial-chemical applications depend ultimately on the method of application, the purpose for dispensing the herbicide or insecticide, and the sensitivity of neighboring crops. For example, when applying some types of herbicides in the vicinity of a sensitive, leafy crop such as lettuce, one should minimize damage to the lettuce crop by leaving a significant distance, of at least 2,000 feet, between treated and sensitive crops. Even with the wind blowing away from a sensitive crop during treatment, a distance of approximately 1,000 feet should be maintained with these types of materials to avoid reversed flows from terrain irregularities or upwind diffusion carrying material to the sensitive crop. Ventilating weather conditions are also desirable during application of herbicides. That is, no overhead warm air ceiling closer than 1,000 feet from the ground should be present. Temperature inversion weather will increase the quantity of airborne material circulating in the confinements of the spray area. Obviously, the specific toxicity of the herbicide and the exposure limits of the sensitive crop would govern the extent of application precaution required.

Another example of how meteorological factors influence spray applications is the determination of suitable or optimum weather conditions for forest area spraying. Studies [13] have shown that the best time for forest spray application is when light winds and stable (inversion) temperature conditions existed. Relative humidity is of critical importance in the case of water base sprays when chemicals are applied to forests. Water base sprays readily evaporate while falling the 200 to 300 feet, which is a typical flight height, used in applying insecticides to forests. The turbulence [13] at treetop height appears to improve the uniformity of deposition across the target area. Studies have demonstrated [13] that the important weather conditions affecting spray deposit and, hence, determination of the suitability of spray conditions are those in the zone from treetop height to the height of spray release. Weather measurements taken at below treetop height do not give an indication of good spray weather and indeed might provide misleading information. With large multi-engine aircraft flying at heights up to 200 m above the trees, it is essential that a complete weather profile be taken to that altitude. The use of large aircraft covering extensive areas also introduces the problem of micro-climate and terrain feature effects which can result in an uneven deposit.

One final example is that of mosquito control. Optimum meteorological conditions for spraying to control mosquitoes are quite different from those for applying a particular herbicide on a field which has an adjacent sensitive crop. The desired meteorological conditions for mosquito control applications are a low level inversion with light winds. The inversion holds the airborne small droplets near the surface, enabling the droplets to collect on the insects. The toxicity of the chemical used is, of course, also important in this application.

It can be seen from the above three examples that optimum or ideal meteorological conditions can be different for different applications. A controlled study is required to first understand the fundamental mechanisms of the spray interaction with the atmosphere. It then will be possible to establish criteria or operating envelopes relative to meteorological conditions for efficient and economical application of chemicals.

6.5 Measurement of Meteorological Parameters During Aerial-Chemical Applications

For approximately thirty years, experimental investigations of the factors affecting the drift and deposit of herbicide and insecticide chemicals from aerial applications have been carried out. As a part of many of these investigations, it has been necessary to examine the micrometeorological factors that affect the transport of aerosols through the atmosphere in order to determine which parameters affect the drift and diffusion most significantly. The results of these investigations have yielded "rule of thumb" guidelines for how meteorological measurements might be used as a means of predicting whether or not prevailing conditions are conducive to the formation of high drift deposits downwind of areas where aerial-chemical applications are being carried out. No systematic experimental program has been carried out and considerable additional research is needed before well-defined operational procedures can be established.

The sensors used in micrometeorological investigations must be sufficiently sensitive to respond to frequency fluctuations in the atmosphere which are on the order of several hundred hertz. Experimental measurement of these frequencies will require hot-film anemometers or other advanced measurement techniques. A brief table of the specifications of the equipment required to conduct a meaningful study are suggested in Table 6-4. This table is by no means exhaustive, however, it illustrates the approximate equipment capabilities necessary to adequately obtain experimental data of sufficient value and accuracy to answer questions now being posed in the operation of agricultural aircraft and by spray applicators. Comments about each variable to be measured are made in Table 6-5. Suggestions concerning what type of instrumentation that should be used to measure the different meteorological parameters of interest are also made. A detailed description of the instrumentation and experimental programs required to support definitive field tests of aerial applications of agricultural chemicals is being carried out in a follow-on effort to this review study. The field tests are currently planned for calendar years 1979 and 1980 at NASA Wallops Flight Center.

TABLE 6-4

LIST OF SIGNIFICANT METEOROLOGICAL PARAMETERS AFFECTING SPRAY DRIFT AND APPROXIMATE EQUIPMENT CHARACTERISTICS AND SPECIFICATIONS RECOMMENDED FOR USE IN MONITORING THESE PARAMETERS DURING AERIAL CHEMICAL SPRAY OPERATIONS

Variable	Range	Threshold
Wind Direction (Angle)	0-360°	0.3 m s^{-1}
Wind Velocity (Vertical)	±30-50 cm s^{-1}	0.3 cm s^{-1}
Wind Velocity (Horizontal)	1-20 m s^{-1}	0.3 m s^{-1}
Relative Humidity	0-100%	1%
Differential Temperature	5-8°C	
Barometric Pressure	28.5-31.0 in. Hg	28.5 in. Hg
Dry Bulb Temperature	-5.0-+50°C	-5.0°C
Normal Incident Radiation (Sun Angle)	0-3000 W/M^2	1 W/M^2
Time of Day (Date)	24 hour	1 sec
Photographic Monitoring	16 mm, 18-64 frames/sec	--
Turbulence (Frequency)	1-200 hz	1 hz
Droplet Diameter	5-1200 μm	∿5 μm

TABLE 6-5

COMMENTS CONCERNING METEOROLOGICAL MEASUREMENTS

(A) The wind direction at flight height should be measured to within a few degrees.

(B) The wind speed should be measured at 0.5, 1.0, 2.5, 4.0, and 10 meters. Measurements at greater heights would be beneficial and should be seriously considered if equipment and towers are readily available. Two general types of measurements should be taken at each height: Low frequency (< 5 hz) measurements to monitor the large eddy fluctuations which affect the general aerosol transport and high frequency (1 hz < f < 200 hz) measurements to monitor the affect of turbulence. It might be feasible to use hot-wire or hot-film anemometers to obtain frequencies up to 200 hz.

TABLE 6-5 (continued)

(C) The relative humidity can be determined by using a sling psychrometer or hygrometer of the desired accuracy.

(D) The differential temperature should be measured at 0.5, 1.0, 2.5, 4.0, and 10 meters (heights as wind velocity and direction measurements) if possible, but not absolutely necessary. A matched calibrated thermistor system will probably be adequate. However, the sensitivity must be adequate enough to detect a temperature differential between the different heights.

(E) The measurement of barometric pressure should not be critical, and measurements performed at a nearby airport or weather station should be adequate.

(F) Dry-bulb temperature should be obtained at as close to dispersal height as possible. For most row crop applications, this height will be 4 to 5 feet or approximately 1.5 meters.

(G) The measurements of incident radiation will probably be an important parameter in determining tracer and chemical degradation. It will also play a role in determining the turbulence and stability.

(H) A device to record the time at which the experimental events take place will be required.

(I) The chemical dispersion process, if visible, should be monitored with a 16 mm movie camera with variable speed capabilities. Time-lapse photography using a 35 mm camera would also prove beneficial and could be easily carried out.

(J) An acoustic radar should be used to obtain a definitive measurement of the inversion layer, if such equipment can be obtained.

(K) Meteorological information gathered by local tower facilities and National Weather Service during the field tests should be utilized.

(L) Equipment capable of obtaining total particle counts should also be used if readily available.

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7.0 REVIEW OF PREVIOUS WORK

7.1 Information Matrix: Aerial-Chemical Applications

The information on aerial-chemical applications in this section covers the time period from approximately 1950 to present. The extent of coverage is by no means all inclusive. A great deal of literature is available, of which, only a small portion is presented here. The material presented is, however, representative and does give a good, brief overview of research in the field of aircraft applications of agriculture chemicals. The matrix as arranged first presents information on the meteorological factors affecting chemical spray drift and then presents information on the use of mathematical prediction models in determining the diffusion of pesticides applied by aircraft. If more detailed information is needed, the references listed in Section 9.0 should be helpful.

1. **REFERENCE:**
<u>Trans. of the ASAE,</u>
Vol. 15, No. 5,
pp. 956-959

INVESTIGATOR(S):
P. Christensen, W. E. Yates
and L. O. Myrup

PUBLICATION DATE:
1972

ORGANIZATION:
Agricultural Engineering Department,
University of California Davis

SPONSOR:
Consumer Protection and
Environmental Health Service,
Food & Drug Administration

2. **OBJECTIVE:** To determine methods by which meteorological measurements might be used as a means of predicting whether or not prevailing conditions are conducive to the formation of high drift deposits.

3. **EXPERIMENTAL TYPE:**
Field

4. **PARAMETERS:**
Wind direction, atmospheric stability, mean wind speed profile, temperature, turbulence level

5. **EXPERIMENTAL PROCESS:**
Measurements of the above parameters were taken using cup anemometers, Gill UVW anemometers, etc., and correlated to drift deposit information.

6. **FACTORS CONSIDERED IN NUMERICAL MODELS:**

7. **CONCLUSIONS:** It was concluded that the stability ratio is a very significant parameter in predicting the formation of high drift deposits. Comparison of stability cases suggested the possibility of using measurements of the angular standard deviation as a means of determining whether or not the prevailing atmospheric conditions might be conducive to the formation of high downwind drift deposits.

8. **COMMENTS:** Further experiments to determine the relation of the spectrum of atmospheric turbulence to drift and diffusion processes probably would be beneficial. Studies involving numerical models of the environment that use the experimental data obtained as input parameters would also be profitable.

1. **REFERENCE:**
Transactions, American Geophysical Union, Vol. 32, No. 6

INVESTIGATOR(S):
F. A. Brooks and C. F. Kelly

PUBLICATION DATE:
December 1951

ORGANIZATION:
University of California Davis

SPONSOR: USDA

2. **OBJECTIVE:**
The development of special instrumentation to study heat transfer from animals and plants, particularly for measuring conduction and radiation

3. **EXPERIMENTAL TYPE:**
Field

4. **PARAMETERS:**
Temperature, moisture, wind velocity and insolation rates

5. **EXPERIMENTAL PROCESS:**

6. **FACTORS CONSIDERED IN NUMERICAL MODELS:**

7. **CONCLUSIONS:**
It was concluded that with an adequate understanding of heat balance, agricultural research findings at one particular location can be extended to other areas of somewhat different climate.

8. **COMMENTS:**
Most of the parameters monitored were obtained in what could be designated as the micro-climate, for example, a stand of grain.

1. **REFERENCE:** Paper No. 77-1504 given at the winter meeting of the American Society of Agricultural Engineers

INVESTIGATOR(S): N. B. Akesson, W. E. Yates and R. E. Cowden

PUBLICATION DATE: December 1977

ORGANIZATION: Agricultural Engineering Department University of California Davis

SPONSOR: Chevron Company

2. **OBJECTIVE:** To develop procedures for evaluating the potential losses during and following pesticide applications

3. **EXPERIMENTAL TYPE:** Field

4. **PARAMETERS:** Spray nozzle type, nozzle pressure, viscosity, surface tension, visco-elasticity, density, vapor pressure

5. **EXPERIMENTAL PROCESS:** To determine what specific physical properties of the various pesticide chemical formulations affect the atomization process and, in turn, try to utilize both formulation factors and mechanical atomizer devices to minimize the production of small size droplets which are susceptible to drift.

6. **FACTORS CONSIDERED IN NUMERICAL MODELS:**

7. **CONCLUSIONS:** Many potential hazardous herbicides may be applied by aircraft either fixed or rotary wing or with ground equipment with minimal chance of causing either spotting or plant damage to sensitive crops if large spray drop-producing equipment is used, which reduces to a minimum the small airborne size drops.

8. **COMMENTS:** There is a need for precise application procedures and considerable care in applying herbicides in areas where sensitive crops can be contacted by airborne drift during application to treated crops.

1. **REFERENCE:**
Trans. of the ASAE, Vol. 16, pp. 378–379

INVESTIGATOR(S):
D. B. Smith and E. D. Threadgill

PUBLICATION DATE:
1973

ORGANIZATION: ARS USDA and Biological & Agricultural Engineering Dept., Mississippi State University

SPONSOR: USDA

2. **OBJECTIVE:** To design a lightweight, small, relatively inexpensive field sampler for obtaining quantitative drop deposits.

3. **EXPERIMENTAL TYPE:**
Laboratory

4. **PARAMETERS:** Droplet size, airflow rate, etc.

5. **EXPERIMENTAL PROCESS:** Collection of spray droplets on filters at different locations inside the collecting device for later analysis

6. **FACTORS CONSIDERED IN NUMERICAL MODELS:**

7. **CONCLUSIONS:** It was concluded from laboratory tests that the sampler should efficiently collect quantitative samples when the spray drops are 50 microns or larger.

8. **COMMENTS:** The device seems to be one alternative for use in the determination of drop size distributions in the field.

1. **REFERENCE:**
TAC TR 70A-066S, USAF SOF TX-58

INVESTIGATOR(S):
W. G. Ehart, et al.

PUBLICATION DATE:
April 1971

ORGANIZATION:
USAF Special Operations Force
Tactical Air Command
Eglin Air Force Base, Florida

SPONSOR:
United States Air Force

2. **OBJECTIVE:** To determine a method of adapting the short boom spray system developed by the U.S. Department of Agriculture to the C-123 aircraft and to determine operational and mechanical characteristics of the system.

3. **EXPERIMENTAL TYPE:**
Field

4. **PARAMETERS:** Altitude, application rate, atmospheric stability, wind velocity

5. **EXPERIMENTAL PROCESS:** Deposition rates and other significant variables were tabulated while monitoring the mosquito mortality rate.

6. **FACTORS CONSIDERED IN NUMERICAL MODELS:**

7. **CONCLUSIONS:** It was concluded that the system is operationally effective with the crosswind drift method of dispersion and the system mechanically adapts to the C-123 with minor modifications.

8. **COMMENTS:** From the results of this experiment, it probably should be recommended that ULV crosswind drift method spray operations be conducted only when there is a positive temperature gradient and the wind velocity is below 10 knots.

1. **REFERENCE:**
U.S. Department of Agriculture,
Line Project No. AE-0-0-2 (DOD)

INVESTIGATOR(S):
L. F. Bouse

PUBLICATION DATE:
April 1, 1966

ORGANIZATION:
Texas Agricultural Experiment Station, Texas A & M University

SPONSOR:
United States Department of Agriculture

2. **OBJECTIVE:** To design and evaluate new herbicides and principles for killing trees, brush and other vegetation and to develop methods of evaluating herbicides and different species of woody vegetation and application techniques.

3. **EXPERIMENTAL TYPE:**
Laboratory and Field

4. **PARAMETERS:**
Droplet size, spray nozzle type and pressure, air speed, physical properties of the spray material, angle of introduction of the spray into the airstream and other factors which affect spray atomization

5. **EXPERIMENTAL PROCESS:** Tests were conducted in a low speed wind tunnel where a single spray nozzle could be observed and aerial spray speeds simulated. Air speed spraying rate, nozzle angle, etc. were easily controlled and varied. Duplication of tests under identical conditions were possible.

6. **FACTORS CONSIDERED IN NUMERICAL MODELS:**

7. **CONCLUSIONS:**
It was concluded that lower nozzle pressures, lower wind speeds and back nozzle positions produced larger drops.

8. **COMMENTS:**
The production and size distribution of droplets is affected by many interdependent parameters and studies probably should be undertaken with each type of chemical now in use.

1. **REFERENCE:** California Agriculture, pp. 4-7, Research Project No. 1423

INVESTIGATOR(S): N. B. Akesson and W. E. Yates

PUBLICATION DATE: December 1961

ORGANIZATION: Agricultural Engineering Dept. University of California Davis

SPONSOR:

2. **OBJECTIVE:** To investigate the effects of weather factors on the drift of chemicals and determine more accurately what part these play on the drift of agricultural pest control chemicals

3. **EXPERIMENTAL TYPE:** Field

4. **PARAMETERS:** Mean wind speed and direction, droplet size distribution, temperature and temperature lapse rate, relative humidity, jet nozzle angle, distance and concentration of drift downwind, etc.

5. **EXPERIMENTAL PROCESS:** Chemicals were dispersed by aircraft. The drop size distributions were obtained using filter papers and glass slides. The amount of residue downwind of the target was measured as a function of distance from the on-target swath.

6. **FACTORS CONSIDERED IN NUMERICAL MODELS:**

7. **CONCLUSIONS:** It was concluded that strong inversion and strong windy turbulent conditions are significant weather parameters which affect drift.

8. **COMMENTS:** The best weather conditions for applications were delineated, but consideration of all of the interdependent parameters affecting spray drift were not investigated.

1. **REFERENCE:**
<u>Trans. of the American Society of Agricultural Engineers,</u> pp. 389-397, Paper No. 64-609A, presented at the winter meeting of the ASAE, December 1964

INVESTIGATOR(S):
W. E. Yates, N. B. Akesson and H. H. Coutts

PUBLICATION DATE:
1966

ORGANIZATION:
University of California Davis

SPONSOR:
United States Public Health Service

2. **OBJECTIVE:**
The evaluation of drift residues from aerial applications

3. **EXPERIMENTAL TYPE:**
Field

4. **PARAMETERS:**
Downwind deposit distance, wind velocity and direction, temperature and temperature gradient, drop size and drop distribution, relative humidity, etc.

5. **EXPERIMENTAL PROCESS:** Chemicals applied to an alfalfa crop are collected on mylar plastic sheets positioned horizontally near the top of the vegetation. Samples are then analyzed using a fluorometer and then appropriately correlated for blank or background interference. The amount of residue as a function of distance downwind from the swath width is then determined using regression analysis.

6. **FACTORS CONSIDERED IN NUMERICAL MODELS:**

7. **CONCLUSIONS:** The regression analysis indicates that the stability ratio is an important parameter which can be used to indicate potential drift problems. It was further concluded that the dimensionless parameter, the Richardson number, applies to a particular ground surface and has a limited value for comparative measurements over surfaces of varying roughnesses.

8. **COMMENTS:**
The data gathering and analysis seem to be tedious and time-consuming; however, more efficient, simpler and yet economical methods which obtain the desired accuracy have not yet been demonstrated.

1. REFERENCE:
Trans. of the ASAE, Vol. 18, pp. 27-34

INVESTIGATOR(S):
C. E. Goering and B. J. Butler

PUBLICATION DATE:
1975

ORGANIZATION: Agricultural Eng. Dept., University of Missouri & Ag. Eng. Dept. University of Illinois

SPONSOR:

2. OBJECTIVE: To measure the effectiveness of a new polymer Nalco-Trol and certain application techniques in reducing drift

3. EXPERIMENTAL TYPE:
Field

4. PARAMETERS: Deposit as a function of distance downwind, drop size, nozzle type and pressure, chemical concentration as a function of distance, temperature gradient, wind turbulence

5. EXPERIMENTAL PROCESS: Chemicals are dispensed by ground rigs as the meteorological and other parameters are monitored.

6. FACTORS CONSIDERED IN NUMERICAL MODELS:

7. CONCLUSIONS: Nalco-Trol spray thickener reduced the amount of drift deposits 49-75% and also increased deposits within the swath. It was also concluded that lowering the nozzle height decreased the drift deposits. Increased air turbulence produced greater spray loss but less downwind deposits.

8. COMMENTS: In order to make comparisons to demonstrate the effect of equipment or formulation changes on drift deposits downwind, experiments should be undertaken in "identical" weather conditions.

1. **REFERENCE:**
<u>Pesticide Management and Insecticide Resistance</u>, 1977, Academic Press, Inc.

INVESTIGATOR(S):
J. A. Armstrong

PUBLICATION DATE:
1977

ORGANIZATION: Chemical Control Research Institute Forestry Directorate Environment, Canada

SPONSOR:

2. **OBJECTIVE:** The determination of suitable weather conditions for forest aerial spraying

3. **EXPERIMENTAL TYPE:**
Field

4. **PARAMETERS:** Droplet distribution, wind speed and direction, turbulence, dry and wet bulb temperature, temperature gradient, barometric pressure, aircraft speed, height and bearing, insecticide emission rate

5. **EXPERIMENTAL PROCESS:** The aircraft dispersed the chemical which was then collected on Kromekote cards for later analysis while meteorological measurements were being taken.

6. **FACTORS CONSIDERED IN NUMERICAL MODELS:**

7. **CONCLUSIONS:** Relative humidity was shown to be of critical importance with water base sprays. It was found that the best time for spray application was with winds between 1 and 5 meters per second and when stable temperature inversion conditions existed. The study demonstrated that weather conditions are important and do affect spray deposits and, hence, determine the suitability of spray conditions.

8. **COMMENTS:** Ideal weather conditions for applying insecticides on forested areas of Canada can be quite different from ideal conditions for application of herbicide in a confined farming area.

1. **REFERENCE:** Trans. of the ASAE, 1974, presented as ASAE paper no. 67-155, 1974

INVESTIGATOR(S): W. E. Yates, N. B. Akesson and R. E. Cowden

PUBLICATION DATE: 1974

ORGANIZATION: University of California Davis

SPONSOR:

2. **OBJECTIVE:** To determine the criteria for minimizing drift residues on crops downwind from aerial applications

3. **EXPERIMENTAL TYPE:** Field

4. **PARAMETERS:** Temperature gradient, mean wind velocity profile, wind direction, relative humidity, temperature, amount of insecticide as a function of distance downwind

5. **EXPERIMENTAL PROCESS:** The spray applications were made with a modified Stearman and Navy N3N aircraft. Each made a number of passes and chemicals with fluorescent tracer present were deposited on mylar sample sheets which were later analyzed using a fluorometer. The pesticide residues on the alfalfa were analyzed using a gas chromatograph.

6. **FACTORS CONSIDERED IN NUMERICAL MODELS:**

7. **CONCLUSIONS:** It was concluded that there was good correlation between residues on the alfalfa and deposits on the mylar sheets. It was concluded that micro-weather conditions such as temperature gradient and wind velocity were important parameters affecting the drift of chemicals.

8. **COMMENTS:** Due to the many interdependent parameters involved in the aerial application of insecticides or herbicides, it is difficult to determine which set of parameters are most important in affecting drift.

1. **REFERENCE:**
Journal of Economic Entomology, Vol. 55, No. 6, pp. 999-1000

INVESTIGATOR(S):
G. B. MacCollom

PUBLICATION DATE:
1962

ORGANIZATION:
University of Vermont

SPONSOR:

2. **OBJECTIVE:** To determine the drift residues on adjacent hay fields while dusting orchards by agricultural aircraft

3. **EXPERIMENTAL TYPE:**
Field

4. **PARAMETERS:** Wind velocity and direction, temperature, particle size and distribution as a function of distance from the orchard, relative humidity, temperature, topography of the area

5. **EXPERIMENTAL PROCESS:** The chemical was dispersed by aircraft while meteorological conditions were monitored and particles were collected on vaseline-smeared slides; the particle diameters were measured at a later time.

6. **FACTORS CONSIDERED IN NUMERICAL MODELS:**

7. **CONCLUSIONS:** Results indicate that drift contamination of forage crops is definitely a problem even under "ideal weather" conditions during application of an insecticide. It was concluded that despite calm, nonturbulent weather conditions, residues were of significant magnitude to be of concern.

8. **COMMENTS:** Much additional work is needed before definitive statements can be made regarding effective particle size, topography of area, temperature and other meteorological factors.

1. REFERENCE:
Journal of Economic Entomology, Vol. 64, No. 3, pp. 718-721

INVESTIGATOR(S):
H. M. Adair, F. A. Harris, M. V. Kennedy, M. L. Laster and E. D. Threadgill

PUBLICATION DATE:
June 1971

ORGANIZATION:
Mississippi State University, Delta Branch Experiment Station, Stoneville, Mississippi

SPONSOR:
USDA Coop. State Research Service, Monsanto Co. and the Nat'l. Agricultural Chemical Assc

2. OBJECTIVE: To determine the drift of methyl parathion aerially applied low volume and ultra-low volume.

3. EXPERIMENTAL TYPE:
Field

4. PARAMETERS: Wind direction and speed, relative humidity, temperature, drop size and distribution as a function of distance from swath

5. EXPERIMENTAL PROCESS: An emulsified concentrate formulation of methyl parathion was applied ultra-low volume and low volume with a Piper PA-18A aircraft. Insecticidal deposits were sampled in the swath and downwind of the swath at various intervals down to 1/2 mile with filter paper sheets and with oil sensitive cards.

6. FACTORS CONSIDERED IN NUMERICAL MODELS:

7. CONCLUSIONS: It was concluded that the ultra-low volume methyl parathion spread over a wider swath and was deposited on the ground sample sheets in higher concentrations downwind of the swath than low volume concentrations.

8. COMMENTS: Due to the limited number of experimental data taken and the lack of temperature gradient and wind profile data plus the interdependency of a good deal of the meteorological parameters which affect drift, definitive statements concerning the results would probably be difficult.

1. **REFERENCE:** Annual Review of Entomology, Vol. 9, pp. 285-318	**INVESTIGATOR(S):** N. B. Akesson and W. E. Yates **ORGANIZATION:** Agricultural Engineering Department, University of California Davis	**PUBLICATION DATE:** 1964 **SPONSOR:**
2. **OBJECTIVE:** To outline the problems relating to the application of agricultural chemicals and any resulting drift residues		3. **EXPERIMENTAL TYPE:** Theoretical
4. **PARAMETERS:**		
5. **EXPERIMENTAL PROCESS:** A review of literature was carried out to delineate the problems of applying agricultural chemicals and the resulting drift residues.		
6. **FACTORS CONSIDERED IN NUMERICAL MODELS:**		
7. **CONCLUSIONS:** It was concluded that although much work has been accomplished, the problem of spray drift will require more experimental data to successfully delineate the problem.		
8. **COMMENTS:** To gain an understanding of the physical problem involved in drift, one should examine the following three factors: (1) distribution equipment and method of use, (2) physical form of the spray, and (3) micrometeorology controlling the materials dispersion.		

1. REFERENCE: Trans. of the ASAE, pp. 613-615, Grant No. UI00284	**INVESTIGATOR(S):** D. R. Heldman **ORGANIZATION:**	**PUBLICATION DATE:** 1968 **SPONSOR:** U. S. Public Health Service

2. OBJECTIVE:
The influence of temperature gradient on aerosol transport

3. EXPERIMENTAL TYPE:
Theoretical and Laboratory

4. PARAMETERS:

Temperature, temperature gradient, particle diameter, relative humidity, airflow characteristics

5. EXPERIMENTAL PROCESS:

Experimental transport coefficients were determined using a two compartment aerosol chamber

6. FACTORS CONSIDERED IN NUMERICAL MODELS:

7. CONCLUSIONS:
That the influence of temperature gradients on aerosol particle flux can be predicted with reasonable accuracy by the Cawood equation

8. COMMENTS:
When one is conducting an experiment of this type, the effects of convection currents should be included.

1. REFERENCE:
Trans. of the ASAE, 1975, Mississippi Agricultural and Forestry Experiment Station, Journal No. 2735

INVESTIGATOR(S):
E. D. Threadgill and D. B. Smith

PUBLICATION DATE:
1975

ORGANIZATION:
Agricultural & Forestry Experiment Station and USDA ARS, Columbia, Missouri

SPONSOR:
USDA

2. OBJECTIVE:
To determine the effects of physical and meteorological parameters on the drift of controlled size droplets

3. EXPERIMENTAL TYPE:
Field

4. PARAMETERS:
Droplet size, horizontal and vertical wind speed, stability ratio, turbulence, temperature relative humidity

5. EXPERIMENTAL PROCESS:
To disperse the spray with ground equipment and measure the drop distribution as a function of distance downwind from the on-target swath

6. FACTORS CONSIDERED IN NUMERICAL MODELS:

7. CONCLUSIONS: It was concluded that in the development of a simulation for pesticide application, a researcher should include the droplet size, a description of atmospheric stability that could include both vertical wind speed and a stability ratio, and possibly the horizontal wind speed.

8. COMMENTS: Caution should be exercised in forming conclusions from graphical presentations in which meteorological parameters are involved. The inherent interdependency of meteorological parameters can quite often lead to erroneous conclusions.

1. REFERENCE:
Trans. of the ASAE, 1974, Missouri Agricultural Experiment Station, Journal No. 6781

INVESTIGATOR(S):
D. B. Smith, C. E. Goering
S. K. Leduc and J. D. McQuigg

PUBLICATION DATE:
1974

ORGANIZATION:
University of Missouri
Columbia, Missouri

SPONSOR:
USDA

2. OBJECTIVE:
To study chemical application decisions based on temporal periods

3. EXPERIMENTAL TYPE:
Field and Theory

4. PARAMETERS:
Distance downwind from swath, drop size, temperature, relative humidity, wind velocity, wind direction, time of day

5. EXPERIMENTAL PROCESS:
To incorporate meteorological data obtained over a 20 year period into a computer model to obtain predicted droplet size and drift distances as a function of the time of day

6. FACTORS CONSIDERED IN NUMERICAL MODELS: Final drop size and distance as a function of dry-bulb temperature, relative humidity and wind velocity, time of day, atmospheric pressure, droplet release height, nozzle pressure, droplet release angle, etc.

7. CONCLUSIONS: Night spraying was found to be statistically superior to day spraying when tested at the 99 percent level of probability and if drift reduction were the only criteria, night spraying would be far superior to day spraying, when most spraying is now done.

8. COMMENTS:
Application of these results apparently will be beneficial for ground applications, but would not be totally beneficial for aerial applications, since FAA regulations permit no night flying.

1. REFERENCE:
<u>Trans. of the ASAE, 1976, Montana Agriculture Experiment Station</u>, Journal Paper No. 611

INVESTIGATOR(S):
F. E. Skoog, T. L. Hanson, A. L. Higgins and J. A. Onsager

PUBLICATION DATE:
1976

ORGANIZATION:
Montana State University and ARS USDA, Montana State University

SPONSOR:
U. S. Department of Agriculture

2. OBJECTIVE:
Systems evaluation and meteorological data analysis for ultra-low volume spraying

3. EXPERIMENTAL TYPE:
Field

4. PARAMETERS:
Wind velocity and direction, temperature gradient, droplet size and distribution, temperature, dispersion parameters such as nozzle type and pressure, flight height, etc.

5. EXPERIMENTAL PROCESS:
Aircraft dispensed the chemical which was collected on Kromekote cards for later analysis

6. FACTORS CONSIDERED IN NUMERICAL MODELS:

7. CONCLUSIONS: Nozzles directed forward and down were always associated with increases in the quantity of small drops as compared with the same nozzle positioned back. Also, it was concluded that wind velocity was not a factor in predicting spray deposits, but only the extent of drift.

8. COMMENTS: The stability ratio was found to be a fairly accurate predictor of vertical spray drift. The best predictions were obtained using all of the variables measured; however, the majority of variables would not be available to the average spray plane operator.

1. **REFERENCE:**
Journal of Applied Meteorology, Vol. 16, pp. 1273-1281

INVESTIGATOR(S):
W. M. Porch and D. A. Gillette

PUBLICATION DATE:
September 1977

ORGANIZATION: Lawrence Livermore Lab, University of California and National Center for Atmos. Research, Boulder, Colorado

SPONSOR:
U.S. Energy Research and Development Administration

2. **OBJECTIVE:** The use of fast response instruments in the comparison of aerosol and momentum mixing in dust storms

3. **EXPERIMENTAL TYPE:**
Field

4. **PARAMETERS:** Visibility, horizontal wind velocity, vertical wind velocity and azimuth, temperature, etc.

5. **EXPERIMENTAL PROCESS:** Fast response, light scattering measurements at two heights during a Texas dust storm were combined with horizontal and vertical wind data to derive and compare aerosol flux estimates using three techniques.

6. **FACTORS CONSIDERED IN NUMERICAL MODELS:**

7. **CONCLUSIONS:** It was concluded that the data shed some light on the complex dependence of wind speed threshold for suspension and aerosol flux in high winds for different surface conditions and soil types. It was believed that the results showed the value of the experimental technique to studies of toxic particulate suspension and deposition by wind.

8. **COMMENTS:** The major results of the analysis were summarized for particles with radii between 0.1 and 1 micron.

1. **REFERENCE:**
Nuclear Safety, Vol. 17, No. 1, Jan.-Feb. 1976

INVESTIGATOR(S):
F. A. Gifford

PUBLICATION DATE:
1976

ORGANIZATION:
Atmospheric, Turbulence and Diffusion Laboratory, Oak Ridge, Tennessee

SPONSOR:

2. **OBJECTIVE:** A review of turbulence diffusion typing schemes

3. **EXPERIMENTAL TYPE:**
Review

4. **PARAMETERS:** Meteorological conditions including temperature gradient, mean wind speed profile, etc.

5. **EXPERIMENTAL PROCESS:** Turbulent diffusion-classifying schemes that have used experimental measurements of mean wind speeds, temperature gradients and other factors relevant in determining diffusion near cities, water bodies, irregular terrain, building wakes, etc. are reviewed.

6. **FACTORS CONSIDERED IN NUMERICAL MODELS:** The parameters mentioned above and other meteorological parameters which were determined from each individual experiment

7. **CONCLUSIONS:** It was concluded that recent environmental concerns have greatly increased the need to calculate air concentrations downwind from various pollution sources. Because concentration depends on diffusion and hence on atmospheric turbulence, turbulence measurements are needed and essential.

8. **COMMENTS:** There are various boundary layer flows that do not fit into any particular class: (1) diffusion under near calm, very stable conditions, (2) diffusion over water, (3) diffusion in the lee of flow obstacles, (4) diffusion near highways, (5) diffusion in irregular and rugged terrain, and (6) diffusion over cities. More research and experimental studies are needed to resolve several of these important problem areas.

1. **REFERENCE:**
<u>Trans. of the American Society of Agricultural Engineers</u>, pp. 74-78, presented as ASAE Paper No. 73-1516, October 1974

INVESTIGATOR(S):
G. E. Miles, E. D. Threadgill, J. F. Thompson and R. E. Williamson

PUBLICATION DATE:
1975

ORGANIZATION:
Purdue University, Mississippi State University & Coastal Plains Experiment Station

SPONSOR:

2. **OBJECTIVE:**
To describe a deposition model (Miles) of spray droplet deposition and also present some of the simulation results

3. **EXPERIMENTAL TYPE:**
Theoretical

4. **PARAMETERS:**
Droplet diameter, target size and orientation, wind velocity, droplet approach angle, fluid properties, drag coefficient

5. **EXPERIMENTAL PROCESS:**
To simulate droplet deposition on bodies with rectangular boundaries

6. **FACTORS CONSIDERED IN NUMERICAL MODELS:**
Droplet diameter, target size and orientation, wind velocity, droplet approach angle, aerodynamic drag coefficient, fluid properties, etc.

7. **CONCLUSIONS:** It was concluded that the results could be used as a guide to researchers investigating chemical applications in crop canopies until difficulties surrounding the collection of empirical data for a wide range of droplet diameters are overcome.

8. **COMMENTS:**
The wide range of drop sizes, wind velocities and plant shape and size will probably make it necessary to use some type of theoretical results in determining the collection efficiency.

1. REFERENCE:
U.S. Army Dugway Proving Ground,
RTDE Project No. 1-T-0-62111-A-H71,
DPG Document No. DPG-TR-M935P

INVESTIGATOR(S):
R. K. Dumbauld, H. E. Cramer
and J. W. Barry

PUBLICATION DATE:
March 1975

ORGANIZATION:
H. E. Cramer Co., Inc. and
U.S. Army Dugway Proving Ground

SPONSOR:
United States Army

2. OBJECTIVE: To discuss in general terms the influence of meteorology on spray operations and the use of mathematical models to predict the behavior of insecticides and herbicides released from aircraft

3. EXPERIMENTAL TYPE:
Review

4. PARAMETERS:

5. EXPERIMENTAL PROCESS: Discuss the use of meteorological prediction models in planning and conducting aerial spray operations.

6. FACTORS CONSIDERED IN NUMERICAL MODELS: Spray delivery system, flight altitude, flight path and swatch width, spray concentration and deposition pattern, meteorological parameters, spray-drift effects, source characteristics, plant properties, etc.

7. CONCLUSIONS: It was felt that work was needed to delineate the requirements to minimize spray drift and to increase the efficiency of spraying in terms of cost and target control. It was further expressed that the generalized nature of the prediction model used was an important feature of the construct and that the basic model format could be universely applicable to all spray problems.

8. COMMENTS: To apply meteorological prediction models to spray operations requires the definition of wind, temperature and possibly humidity fields in the area of spray operation. Although such a measurement program seems ambitious, growing prerequisite documentation for the registering of insecticides and environment control of spray operations by Government agencies indicate that further experimental measurements be made.

1. **REFERENCE:** Nuclear Safety, Vol. 13, No. 5, pp. 391-402	**INVESTIGATOR(S):** F. A. Gifford, Jr.	**PUBLICATION DATE:** 1972
	ORGANIZATION: Air Resources Atmospheric Turbulence and Diffusion Lab., Oak Ridge, Tennessee	**SPONSOR:** NOAA

2. **OBJECTIVE:** The determination of atmospheric transport and dispersion over cities

3. **EXPERIMENTAL TYPE:** Review

4. **PARAMETERS:** Average wind speed, intensity of air turbulence, cross wind nd vertical standard deviations, cloudiness, amount of solar radiation, strength of the mean wind, atmospheric stability, aerodynamic and surface roughness, heat capacity

5. **EXPERIMENTAL PROCESS:** The effect of enhanced surface roughness and heat capacity over cities and these effects on the micrometeorology of an urban atmospheric boundary layer were briefly summarized. Diffusion models for urban sources are also reviewed.

6. **FACTORS CONSIDERED IN NUMERICAL MODELS:**
Those parameters mentioned above are considered in the numerical models

7. **CONCLUSIONS:** Dispersion is enhanced by the increased urban roughness, although transport by the mean wind is slightly decreased by the aerodynamic drag. The temperature gradients in the first few 100 feet over cities are observed to be adiabatic.

8. **COMMENTS:** As a rough rule-of-thumb, the increased vertical mixing that takes place over cities can be approximated by a shift in the letter classification of σ_z, according to Pasquill's well-known scheme of one letter category, in the unstable direction.

1. **REFERENCE:** USDA Forest Service General Technical Report, PSW-15/1976	**INVESTIGATOR(S):** H. E. Cramer and D. G. Boyle **ORGANIZATION:** Cramer Co., Salt Lake City, Utah and Desert Test Center, Fort Douglas, Utah	**PUBLICATION DATE:** 1976 **SPONSOR:** U. S. Department of Agriculture
2. **OBJECTIVE:** To study the micrometeorology and physics of spray particle behavior through the use of computer modeling		3. **EXPERIMENTAL TYPE:** Theoretical
4. **PARAMETERS:** Release and source emission parameters, meteorological parameters, terrain and vegetative parameters		
5. **EXPERIMENTAL PROCESS:** To use the state of the art expressions reflecting the best available knowledge in a computer model to provide information on spray dispersion		
6. **FACTORS CONSIDERED IN NUMERICAL MODELS:** Peak concentration term, a long wind term, edge effects term, edge effects term, vertical term and depletion term		
7. **CONCLUSIONS:** It was concluded that the accuracy of the model prediction is limited principally by the accuracy and adequacy of the source and meteorological inputs.		
8. **COMMENTS:** The deposition of aerial sprays on vegetation or insects is apparently the result of many different processes that are not yet well understood.		

1. **REFERENCE:**
Agricultural Meteorology, Vol. 15, pp. 257-271

INVESTIGATOR(S):
D. H. Bache and W. J. D. Sayer

PUBLICATION DATE:
1975

ORGANIZATION: Nottingham University and Central Electricity Generating Board Scientific Service Center

SPONSOR:

2. **OBJECTIVE:**
To determine the transport of aerial spray by use of computer models

3. **EXPERIMENTAL TYPE:**
Theoretical and Experimental

4. **PARAMETERS:**
Maximum concentration, cloud growth rate, turbulent intensity, distance from release height, etc.

5. **EXPERIMENTAL PROCESS:** Comparison of a simple model representing deposition from a sedimenting cloud diffusing about its center of gravity was compared with tracer distributions obtained from aerially released line sources in the lowest 15 m of the atmosphere.

6. **FACTORS CONSIDERED IN NUMERICAL MODELS:**
Parameters mentioned above are considered in the numerical models.

7. **CONCLUSIONS:** For clouds of light particles, it was concluded that the distribution was characterized by the position of maximum concentration, which occurs at a distance proportional to the release height and inversely proportional to the turbulent intensity.

8. **COMMENTS:**
Estimates were provided for ground deposition from line sources oriented parallel to and perpendicular to the wind direction.

1. **REFERENCE:**
Agricultural Meteorology, Vol. 15, pp. 371-377

INVESTIGATOR(S):
D. H. Bache and S. Uk

PUBLICATION DATE:
1975

ORGANIZATION:
Nottingham University and
Cranfield Institute of Technology

SPONSOR:

2. **OBJECTIVE:**
To determine the transport of aerial sprays within a crop canopy

3. **EXPERIMENTAL TYPE:**
Theoretical and Experimental

4. **PARAMETERS:**
Droplet size and distribution, foliage parameters, wind speed and direction, etc.

5. **EXPERIMENTAL PROCESS:**
A simple model based on canopy structure was developed to explain the vertical distribution of clouds of droplets in a crop canopy

6. **FACTORS CONSIDERED IN NUMERICAL MODELS:**
Those factors indicated above were considered in the numerical models

7. **CONCLUSIONS:**
The results obtained suggested that collection by sedimentation was the predominant mechanism for the capture of droplets with diameter greater than 40 microns by a cotton canopy.

8. **COMMENTS:**
The results suggested the average foliage impaction efficiencies are low ($E < 0.1$).

1. REFERENCE:
Agricultural Meteorology,
Vol. 15, pp. 379–383

INVESTIGATOR(S):
D. H. Bache

PUBLICATION DATE:
1975

ORGANIZATION:
Nottingham University, School
of Agriculture

SPONSOR:

2. OBJECTIVE:
To determine the influence of micro-climate on crop spraying

3. EXPERIMENTAL TYPE:
Theoretical and
Experimental

4. PARAMETERS: Droplet size and distribution, spray height, turbulence intensity, sedimentation, velocity, and average wind speed between the ground and release height, wind profile, stability conditions

5. EXPERIMENTAL PROCESS: The work reviews the implication of previous studies for practical crop spraying from aircraft and gives examples of the influence of the micro-climate on the choice of droplet sizes and spraying heights.

6. FACTORS CONSIDERED IN NUMERICAL MODELS:
The parameters mentioned above are used as factors

7. CONCLUSIONS:
There are advantages in using sprays composed of small droplets. The micrometeorological measurements made over cotton suggest that maximum droplet diameter should be about 60 microns.

8. COMMENTS:
Optimum flying heights should be interpreted with caution since they are characteristic of the particular crop for which measurements are made.

1. **REFERENCE:** USDA Forest Service General Technical Report, PSW-15/1976	**INVESTIGATOR(S):** N. B. Akesson and W. E. Yates **ORGANIZATION:** University of California Davis	**PUBLICATION DATE:** 1976 **SPONSOR:** USDA

2. **OBJECTIVE:** To delineate and discuss the physical parameters related to pesticide application

3. **EXPERIMENTAL TYPE:** Field and Review

4. **PARAMETERS:** Drop size and frequency distributions, dispersion parameters, meteorological parameters, in particular wind velocity and direction, temperature and temperature gradient

5. **EXPERIMENTAL PROCESS:** Review of dispensing equipment available which produces various size droplets ranging from aerosols to coarse sprays. An assessment of actual field deposits and insect contact rates is also presented. An assessment of local meteorology, particularly temperature inversion, which strongly affects spray dispersion, is also given.

6. **FACTORS CONSIDERED IN NUMERICAL MODELS:**

7. **CONCLUSIONS:** That the basic parameters controlling the success or failure of a vector control operation are (1) temperature gradient or change with height, (2) wind velocity and wind velocity gradient with height, (3) wind direction during spraying, and (4) relative humidity as it relates to spray drop evaporation.

8. **COMMENTS:** The most significant of the factors listed above is the temperature gradient.

1. REFERENCE:
Trans. of ASAE, 1972, Missouri Agriculture Experiment Station, Journal Paper No. 7023

INVESTIGATOR(S):
C. E. Goering, L. E. Bode and M. R. Gebhardt

PUBLICATION DATE:
1972

ORGANIZATION:
University of Missouri, Columbia, Missouri

SPONSOR:
USDA

2. OBJECTIVE:
To mathematically model spray droplet deceleration and evaporation

3. EXPERIMENTAL TYPE:
Theoretical and Experimental

4. PARAMETERS: Drop size and shape, properties of the air, drag coefficient, velocity of the particle relative to the medium, dry-bulb temperature, relative humidity, atmospheric pressure, direction and magnitude of the wind, nozzle pressure and direction, direction of droplet dispersion, flight height, etc.

5. EXPERIMENTAL PROCESS:
The above parameters were incorporated into a mathematical model to determine the spray droplet deceleration and evaporation. Verification of the numerical model was carried out experimentally.

6. FACTORS CONSIDERED IN NUMERICAL MODELS:
The parameters mentioned above were considered

7. CONCLUSIONS: It was concluded that droplets 45 microns in diameter or less had a short life expectancy in air at 70°F and 50 percent relative humidity. Droplets 45 microns or less in diameter would disappear within 6 inches of the nozzle. Results indicate that the rate of diameter change is inversely proportional to the diameter, thus, the smaller the droplet the more rapidly it disappears.

8. COMMENTS:
With an induced air current, the droplets most probably would be carried rapidly enough that only a small amount of evaporation would occur within a short distance of the nozzle.

1. REFERENCE:
Lectures on Air Pollution and Environmental Impact Analyses, American Meteor. Society

INVESTIGATOR(S):
F. Pasquill

PUBLICATION DATE:
1975

ORGANIZATION:

SPONSOR:

2. OBJECTIVE:
To review the basis for generalization of the dispersion of material in the atmospheric boundary layer

3. EXPERIMENTAL TYPE:
Review

4. PARAMETERS:
Wind direction, velocity, roughness length, pressure, friction velocity, air density, acceleration due to gravity, specific heat of air, etc.

5. EXPERIMENTAL PROCESS:
To summarize the basis on which it is possible to prescribe general laws for the action of the atmospheric boundary layer in dispersing and diluting pollutants

6. FACTORS CONSIDERED IN NUMERICAL MODELS:
Those factors mentioned above with other parameters most commonly used in describing the atmospheric boundary layer and the dispersion of materials on pollutants.

7. CONCLUSIONS:
Realistic estimates of cross wind spread over the first 10 km or so of travel from a continuous source in the mixed layer may be made on the basis of statistical theory.

8. COMMENTS:
More general similarity considerations for the vertical transfer in the mixed layer should be made which include free convection modeling for stably capped mixed layers.

1. REFERENCE:
Lectures on Air Pollution and Environmental Impact Analysis, American Met. Society

INVESTIGATOR(S):
F. A. Gifford

PUBLICATION DATE:
1975

ORGANIZATION:
Air Resources Atmospheric Turbulence and Diffusion Lab., Oak Ridge, Tennessee

SPONSOR:
NOAA

2. OBJECTIVE:
To review the atmospheric dispersion models for environmental pollution applications

3. EXPERIMENTAL TYPE:
Review

4. PARAMETERS:
All those parameters normally considered in modeling dispersion of pollution in the atmosphere

5. EXPERIMENTAL PROCESS:
The work is principally concerned with mathematical cloud or plume models describing acute effects of pollution, i.e., those arising from comparatively high concentration levels.

6. FACTORS CONSIDERED IN NUMERICAL MODELS:
This review work encompasses a majority of the factors considered in many of the numerical models being used to determine the dispersion of pollutants in the atmosphere.

7. CONCLUSIONS: It was concluded that mathematical model studies of many exceptional cases, backed up by adequate experimental diffusion trials in the real atmosphere, are going to be necessary before many outstanding modeling problems can be fully resolved.

8. COMMENTS: Modeling difficulties exist for models of diffusion over water, irregular rugged terrain in very stable conditions, and in other situations of great practical importance.

1. REFERENCE:
Paper No. 77-1503, presented at the winter meeting of the ASAE, December 1977

INVESTIGATOR(S):
R. W. Tate

PUBLICATION DATE:
1977

ORGANIZATION:
Delavan Corporation,
West Des Moines, Iowa

SPONSOR:
Delavan Corporation

2. OBJECTIVE:
To investigate droplet size distributions for drift reduction nozzles

3. EXPERIMENTAL TYPE:
Laboratory

4. PARAMETERS: Nozzle type and pressure, spray angle

5. EXPERIMENTAL PROCESS: Two different methods were utilized to determine droplet size. The first is a collection technique which uses dyed water which is sprayed into a solvent and then photographed at high magnification for later data reduction. The second is an "in situ" photographic technique.

6. FACTORS CONSIDERED IN NUMERICAL MODELS:

7. CONCLUSIONS:
The laboratory measurements of droplet size identified several important characteristics of drift reduction nozzles. A drastic reduction in percentage of fine drops was realized.

8. COMMENTS:
Drift reduction by reducing the number of fine droplets in the spray distribution is indeed possible; however, at times, smaller droplets are desired for a particular application.

1. REFERENCE:
A.I.Ch.E. Journal, Vol. 7, No. 4, pp. 615-619

INVESTIGATOR(S):
L. B. Torobin and W. H. Gauvin

PUBLICATION DATE:
1961

ORGANIZATION:
Pulp and Paper Research Institute of Canada and McGill University, Montreal

SPONSOR:
Scientific Research Bureau, Trade & Commerce Department, Province of Quebec

2. OBJECTIVE:
The determination of drag coefficients of single spheres moving in steady and accelerated motion in a turbulent fluid

3. EXPERIMENTAL TYPE:
Experimental and Theoretical

4. PARAMETERS:
Droplet size, droplet density, droplet velocity, turbulence parameters

5. EXPERIMENTAL PROCESS: Theoretical considerations were compared with wind tunnel tracer particle velocity measurement techniques which were developed to allow a quantitative determination of the drag coefficients of single particles moving in both steady and accelerated motion.

6. FACTORS CONSIDERED IN NUMERICAL MODELS:

7. CONCLUSIONS: Increasing free stream vorticity relative to the motion of generating the particle boundary layer and wake will at first cause a moderate increase and then a sharp decrease in the particle drag coefficient.

8. COMMENTS: A transition theory for the system investigated was presented, which predicts that the product of the critical Reynolds number and the square of relative intensity should be a constant; these results are supported by the experimental data obtained.

1. REFERENCE:
Journal of Applied Meteorology, Vol. 16, No. 11, ATDL Contribution File No. 77/10

INVESTIGATOR(S):
C. J. Nappo, Jr.

PUBLICATION DATE:
November 1977

ORGANIZATION:
Air Resources, Atmospheric Turbulence and Diffusion Laboratory

SPONSOR:
National Oceanic and Atmospheric Administration (NOAA)

2. OBJECTIVE:
Determine the mesoscale flow over complex terrain

3. EXPERIMENTAL TYPE:
Field

4. PARAMETERS:
Horizontal mean wind velocity, stability conditions

5. EXPERIMENTAL PROCESS:

The horizontal variability of the wind field was measured by forming: (1) the standard deviation of the wind speed, σ_s and direction, σ_θ, and (2) the ratios of horizontal eddy to mean kinetic energy.

6. FACTORS CONSIDERED IN NUMERICAL MODELS:

7. CONCLUSIONS: It was theorized that during unstable conditions, horizontal uniformity of the wind resulted from the homogeneous action of the time average convective overturning while during stable conditions, horizontal variability resulted from flow channeling and drainage.

8. COMMENTS: The experiments were attempts at sampling the vertical variations of the mesoscale flow over complex terrain. The analysis showed the complex structure of this flow; the question of how to generalize these results, however, remains.

1. REFERENCE:
Report on ATDL Research on Meteorological Effects of Thermal Energy Releases, Aug. 1, 1976 through Sept. 30, 1977, U.S. Dept. of Commerce, ATDL Contribution File No. 77/27

INVESTIGATOR(S):
S. R. Hanna, K. S. Rao and R. P. Hosker

PUBLICATION DATE:
November 1977

ORGANIZATION:
Environmental Research Laboratories, Oak Ridge, Tennessee

SPONSOR:
National Oceanic and Atmospheric Administration

2. OBJECTIVE:
To apply several new sets of data from four separate sites to recent ATDL plume and cloud growth models

3. EXPERIMENTAL TYPE:
Theoretical and Experimental

4. PARAMETERS:
Surface features such as relative humidity, wind direction, velocity and angle, plus power park parameters such as total waste, heat flux, etc.

5. EXPERIMENTAL PROCESS:
Time lapse photography of the plumes were taken while parameters were being measured

6. FACTORS CONSIDERED IN NUMERICAL MODELS:
The initial parameters discussed above plus plume rise, plume dimensions and maximum liquid water contents, etc.

7. CONCLUSIONS:
It was concluded that the model predictions show good qualitative agreement with available observations for smaller industrial sources, and the calculated mean and turbulence quantities have physically realistic distributions.

8. COMMENTS:
There are too few field observations with sufficient detail to provide a demanding test of the mean profiles and turbulence flux predictions.

7.2 Information Matrix References

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8.0 CONCLUSIONS

A significant factor controlling the success or failure of an aerial-chemical spray operation is the local meteorology. It is probably the most universally relevant and yet the least understood of the several factors dominating the application of chemicals by aircraft. Numerous experiments have been performed in an attempt to delineate the fundamental factors influencing drift of aerially applied pesticides. However, no extensive systematic study of parameters such as aircraft type and aerodynamics, application equipment, and meteorological conditions has been carried out.

Previous experiments in aerial applications of agricultural chemicals have illustrated that many meteorological variables collectively determine the degree of pest control, the performance of the spray applicators, the amount of chemical deposited in the on-target swath, and the amount of chemical that drifts onto adjacent locations. The majority of variables are, however, interdependent and, consequently, it is difficult to study the effect of each individual parameter. Previous research efforts have answered some questions; but the overall problem of attaining sufficient weed, brush, or insect control while substantially reducing drift still remains. There is a definite need for a systematic experimental research project to delineate, measure, and quantify the significant meteorological parameters which contribute to agricultural chemical drift. The results of such a comprehensive study could be used to minimize or control hazardous agricultural chemical contamination of neighboring sites while placing the correct amount of chemical at the location desired.

Many aspects of the drift problem can only be studied by means of field tests. However, because of the complex variable interdependency factors, the use of mathematical models will be helpful. Mathematical modeling should be used as a tool to aid in interpreting field results, designing measuring equipment, and predicting the potential for drift in a given situation, as well as for providing operational mission guidance and tools for the registration of aerial applied chemicals.

A realistic simulation of an agricultural spraying operation must consider the air motion due to natural surface winds and meteorological turbulence, as well as air currents generated by the motion of the aircraft. Ideally, the model should be formulated to include spray and spray equipment characteristics, three-dimensional droplet motion, and rate of mass transfer from the droplets due to evaporation.

Input data for the simulation should include the meteorological conditions, the physical and mass transport properties of the spray liquid, and the applications parameters (aircraft aerodynamics, droplet initial size, wind speed, etc.).

Existing numerical models are, of course, inherently interim but do reflect the best available knowledge. Appropriate source and meteorological information is fragmentary or completely lacking in many instances. Due to inadequacies in existing measurements, the amount of rigorous model validation to date is disappointingly small. However, the present knowledge in model validation has demonstrated that the overall framework is adequate and that the accuracy of model predictions is limited principally by the adequacy and accuracy of the source and meteorological inputs.

An experimental examination of the micrometeorological factors that affect the transport of aerosols through the atmosphere is necessary to determine which of the parameters most significantly affect the diffusion process. The results of such investigations could be used to ascertain which prevailing meteorological conditions are conducive to the formation of high drift deposits. This valuable information will help to delineate the conditions which will enable minimization and perhaps drift control of aerially applied chemicals.

Any adequate measuring system must produce wind, temperature, and humidity data, as well as data on other parameters, for the immediate vicinity of the field experiment. Instruments must have response characteristics capable of measuring the significant fluctuations in these parameters which affect the diffusion of the particles being investigated. Unfortunately, most previous experiments have not been extensive enough to obtain sufficient data to adequately assess the overall effect of meteorological parameters on agricultural chemical drift. Constraints such as time, economics, and instrument capability have been responsible in this regard. The present effort has delineated the significant meteorological parameters which need to be measured and defined the approximate instrument capabilities required.

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16. Abstract

The significant meteorological parameters affecting the aerial application of agricultural chemicals from aircraft are investigated. The ambient wind field and temperature gradient were found to be the most important parameters in this regard. The results indicate that the majority of meteorological parameters affecting dispersion are interdependent and the exact mechanism by which these factors influence the particle dispersion is largely unknown. The report defines the type and approximate range of instrumented capabilities for a systematic study of the significant meteorological parameters influencing aerial applications.

Current mathematical dispersion models are also briefly reviewed. Unfortunately, a rigorous dispersion model which can be applied to aerial application is not available.

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