COLLECTION KERNELS FOR THE CAPTURE OF SILVER IODIDE NUCLEI BY CLOUD WATER DROPS

L. A. Mathews and P. St.-Amand

Earth and Planetary Sciences Division
Naval Weapons Center
China Lake, California

ABSTRACT

Capture of AgI nuclei by cloud drops, through the microphysical processes of inertial and interceptive impaction, Brownian diffusion, and wake capture is expressed in terms of a collection kernel as a function of AgI nuclei and cloud drop radii. Also, the effect of phoretic forces and turbulence on the collection kernel is assessed.

For the capture of 0.01 to 10 μm radius AgI nuclei by cloud droplets with radii 50 μm or greater, the collection kernels are greater than 10^{-6}. These kernels are large enough to bring practical concentrations of AgI nuclei into contact with cloud drops at a rate such as to cause rapid freezing of cloud water accompanied by a large heat release if the updraft portion of a cloud is seeded. However, impractically large amounts of nuclei may be required to contact droplets in the downdraft portion of a cloud, and more so, if drop evaporation is rapid and the drops are positively charged.

INTRODUCTION

The rate at which AgI nuclei are captured by cloud water drops is needed in an updated and useable form to improve cloud seeding techniques. If this rate of capture as well as the rate of dissolution of nuclei are used in cloud optimization models, seeding within cloud can be conducted to yield maximum rainfall at minimum cost. That is, one would be able to know exactly when and where to inject the correct nucleant particle size and concentrations into a cloud.

The rate of capture of nuclei is best described in terms of the collection kernel which is used in the stochastic collection equation (e.g., Scott {1967}, Berry {1968}, Drake {1970} and Gillespie {1972}). This collection kernel, or the collection volume swept out per unit time per drop, is defined as

$$K(A,a) = \pi \ (A+a)^2 \bar{E}(A,a) \ (V_A - V_a), \tag{1}$$

where A and a are the drop and droplet or particle radii, respectively.

$\bar{E}(A,a)$ is the "collection efficiency" factor, which can account for the fact that owing to microphysical processes such as Brownian diffusion, hydrodynamic impaction, wake capture, turbulence, electrophoresis, thermophoresis and diffusiophoresis the collection volume will differ from the geometrical sweep-out volume. V_A and V_a are the velocities of the drop and droplet or particle, respectively. In this paper, the collection kernel will include only the microphysical processes of inertial and interceptive impaction, Brownian diffusion, and wake capture. Also, the above mentioned collection efficiency is assumed to be equal to the collision efficiency since coalescence efficiency has been shown to be close to unity for radius ratios less than 0.1 (see, e.g., Levin et al., 1973).

The radius of nuclean particles should lie somewhere between 0.05 and 0.2 μm for practical cloud seeding. Smaller and larger particles should be avoided because of short lifetimes due to solubility (Mathews, et al., 1972) and economics, respectively. However to compare past cloud seeding operations, consideration should be given to the collection of nucleant particles having radii from 0.01 to 10 μm, since all these sizes have been used. For example, particles having radii 1 to 10 μm should be included since dissolution of small particles may occur so rapidly with some poor formulations of AgI smoke, that only large particles remain as effective nuclei.

Cloud drops, which contact nuclei and subsequently freeze, range in size from 5 to 1,000 μm in radius. The larger drops may very well exist in updrafts since they offer the only explanation for the large liquid water contents found there. Furthermore, updrafts of 30 ft/sec (9m/sec) will allow drops with radii up to 1,000 μm to remain suspended.

In order to calculate the collection kernel for the above ranges of cloud drops and nucleant particles, it is necessary to obtain collision efficiency over a wide range of physical conditions. Brownian diffusion is a significant capture mechanism for small particles, i.e., for a $\lesssim$ a 0.2 μm, rapidly decreasing with increase in particle radii. However, the mechanism of wake capture can in some cases predominate over Brownian diffusion for these small particles, e.g., for AgI particles having 0.07 to 0.3 μm radii, interacting with falling drops having Reynolds numbers from 100 to 450. Interception impaction tends to be a significant capture mechanism for particles having radii from about 0.2 to 1 μm while, depending on drop Reynolds number, inertial impaction can be significant for AgI particles with radii as small as 0.3 μm.

Collection kernels are presented here for the interaction of water drops with particles or droplets having a density, ρ_p, of 1 gm/cm^3 as well as those for AgI (i.e., ρ_p = 5.67 gm/cm^3). The kernels while being useful for cloud seeding and fog scavenging studies may be applicable, possibly with some interpolation in regard to particle density, to pollution scavenging studies.

COLLISION EFFICIENCIES

In the absence of phoretic forces and turbulence, the collision efficiency for the capture of a small particle by a water drop depends on five dimentionless parameters or $E = E(N_{Re}, N_{Sc}, p, \alpha, N_{Stk})$. The parameters are:

drop Reynolds number, $N_{Re} = 2AV_A\rho_g/\mu_g$

Schmidt number, $N_{Sc} = \mu_g/\rho_g D$

interception parameter, $p = a/A$

viscosity ratio, $\alpha = \mu_w/\mu_g$

and Stokes number, $N_{Stk} = 2a^2 \rho_a V_A C/9\mu_g A$

where:

D = diffusion coefficient of particles

ρ_g = air density

ρ_a = particle density

μ_g = air viscosity

μ_w = water viscosity

C = Cunningham factor $(=1+B\lambda/a)$

B = slip correction coefficient (Davies, 1945) and

λ = mean free path of air molecules

The effect of Brownian diffusion, interception, and inertial impaction on collision efficiency depend functionally on the following groups of dimensionless parameters:

$\Psi_1(N_{Re},N_{Sc})$, $\Psi_2(N_{Re}, \rho, \alpha)$ and $\Psi_3(N_{Re},N_{Stk})$, respectively.

a. Brownian Diffusion and Interception for All Drop Reynolds Numbers.

Collision efficiency versus water drop radius is plotted for particle radii of one micron and less in Figs. 1 and 2. Fig. 1 gives collision efficiencies for Brownian diffusion only. Fig. 2 gives combined collision efficiencies for Brownian diffusion and interception i.e., $E = E_B+E_I$. These combined collision efficiencies, E, are based on the assumption that no synergism exists between Brownian diffusion and interception and there are no inertial effects.

For water drop radii of 5 to 20 microns or for viscous flow, collision efficiencies are shown as solid lines on the left hand side of both Figs. 1 and 2. The Brownian diffusion only values are obtained from an equation given by Zebel (1968) or

$$E_B = 3.18\ Pe^{-2/3} \tag{2}$$

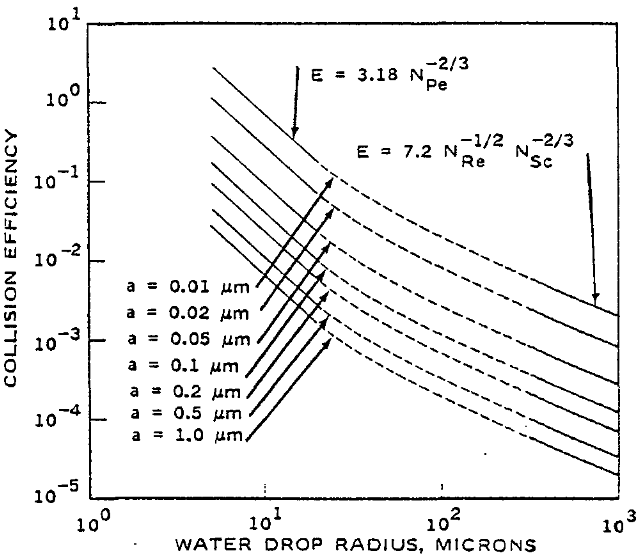

FIGURE 1. Collision efficiency for Brownian diffusion only versus water drop radius with the parameter, particle radius, ranging from 0.01 to 1 μm. This plot shows the interpolation between the theories for viscous flow and for drop Reynolds numbers greater than 100.

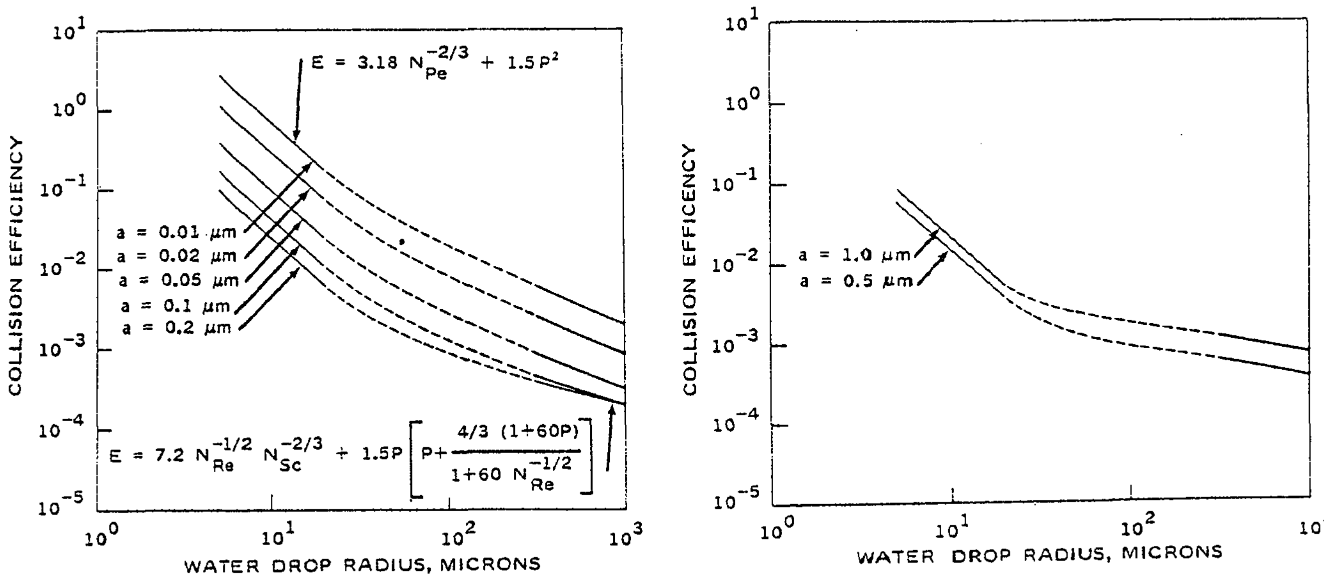

FIGURE 2. Collision efficiency for Brownian diffusion plus interception versus water drop radius with the parameter, particle radius, ranging from 0.01 to 1 μm. This plot shows the interpolation between the theories for viscous flow and for drop Reynolds numbers greater than 100.

where Peclet number,

$$N_{Pe} = \frac{AV_A}{D} \tag{2a}$$

and where D is the Brownian diffusion coefficient. Note that Peclet number as defined here is equal to one half of the product of the Reynolds and Schmidt numbers. Also, for these small drops, falling with very small Reynolds numbers, Fuchs (1964) gives collision efficiency for the interception effect due to particle radius as

$$E_I = 1.5\ p^2 \tag{3}$$

where $p = a/A$. Internal circulation effects on collision efficiency, described by the viscosity ratio, α, are not significant in the case of these small droplets, and thus, no functional dependence on α is given here.

The collision efficiencies shown as solid curves on the right hand side of Figs. 1 and 2 are for water drops falling with Reynolds numbers of 100 or greater. These Reynolds numbers correspond to water drops of 310 micron radius or greater falling in air having a temperature of -2°C and a pressure of 800 mb. The Brownian diffusion collision efficiencies for Re>100 were found by making use of dimensional similarity and experimental Sherwood numbers, N_{Sh}. Sherwood number is equivalent to the flux of particles to a moving sphere normalized by the flux to a stationary sphere. Fuchs (1964) shows that the rate of deposition on a stationary sphere is equal to

$$\phi = 4\pi DAn \tag{6}$$

where n is the particle concentration. Thus, the rate of deposition on a sphere having a finite velocity is $\phi\ N_{Sh}$. Since collision efficiency is defined as the ratio of particles actually deposited to those particles deposited if geometric sweepout were possible,

$$E_B = \frac{\phi N_{Sh}}{\pi A^2 V_A n} \tag{7}$$

or

$$E_B = \frac{4N_{Sh}}{N_{Pe}} \tag{7a}$$

Aksel'rud (1953 experimentally found for Sherwood number the expression

$$N_{Sh} = 0.8\ N_{Re}^{\ 1/2} N_{Sc}^{\ 1/3} \tag{8}$$

for $600<N_{Re}<2600$ and $N_{Sc} = 2.3 \times 10^6$ for the dissolution rate of benzoic acid spheres in oil. A similar formula was found by Gardner and Suckling (1958) in experiments involving the dissolution of spheres of adipic acid and benzoic acid in water for $100<N_{Re}< 700$ and $N_{Sc} \; 10^3$. Their formula for Sherwood number was similar to Eq. (8) except it contained the coefficient 0.95 instead of 0.8. Since we desire collision efficiencies for water drops having Reynolds numbers of 100 to 895 interacting with submicron particles with Schmidt numbers from 10^3 to 10^6, the Sherwood number to be substituted in Eq. (7a) was approximated by

$$N_{Sh} = 0.9 \, N_{Re}^{1/2} N_{Sc}^{1/3} \tag{9}$$

The coefficient 0.9 is weighted more towards the experimental data of Gardner and Suckling because of their Reynolds numbers extending over most of our range of interest. The collision efficiency due to Brownian diffusion can be expressed as

$$E_B = 3.6 \, \frac{N_{Re}^{1/2} N_{Sc}^{1/3}}{N_{Pe}} = 7.2 \, N_{Re}^{-1/2} N_{Sc}^{-2/3} \tag{10}$$

Slinn (1974) expresses the interception contribution to collision efficiency as

$$E_I = 4p \, \left(p + \frac{1+2\alpha p}{1+\alpha N_{Re}^{-1/2}}\right) \tag{11}$$

where $\alpha = \mu_w/\mu_g \simeq 60$.
This equation accounts for internal circulation of the drop at $N_{Re} >> 1$. However, we have noted an error in its derivation. Slinn lets the critical impact parameter, y_c, equal the particle diameter rather than the particle radius. Critical impact parameter is defined by Mason (1971) as the initial horizontal separation of the particle and drop centers on a grazing trajectory. Because of this error, Slinn gets $E_I \gtrsim 4p^2$ rather than $E_I \gtrsim p^2$ for his estimation at Stokes flow conditions. Fuchs (1964) finds for Stokes flow that $E_I = 1.5p^2$. Also, for large Reynolds number, Slinn considers only the lowest "2a" of the boundary layer is devoid of particles rather than the lowest "a" of the boundary layer being devoid of particle <u>centers</u> due to interception. Thus, we obtain a corrected form of Equation (11) or

$$E_I = 1.5p \, (p + \frac{4/3(1+\alpha p)}{1+\alpha \, N_{Re}^{-1/2}} \tag{12}$$

For comparison purposes, collision efficiencies calculated from the theory of Suneja (1973) for potential flow are shown in Fig 3h for 1,000 μm radius drops (N_{Re}= 895). Note that there is a fair agreement between the collision efficiencies of Suneja and those obtained from the sum of Eqs. (10) and (12). In actuality, a finite Reynolds number consideration, as discussed by Suneja, would tend to lower his collision efficiencies. His values are limited to particle radii smaller than 0.05 μm since larger particles would affect the flow field.

In Figs. 1 and 2, the transition range of drop Reynolds numbers, i.e., $0.1<N_{Re}<100$, collision efficiencies for Brownian diffusion and Brownian diffusion plus interception are approximated by dashed curves drawn between the two theoretical expressions for each particle radius.

b. Inertial Impaction and Wake Capture.

Beard and Grover (1974), through the use of numerical stream functions of LeClair et al. (1970), present collision efficiency versus Stokes number for small raindrops colliding with micron size particles. Their results account for collision geometry or the interception effect as well as the inertia of the particles. In Figs. 3a through 3f for Reynolds numbers of 1, 10, 20, 100, 200 and 400, we have plotted collision efficiency versus AgI particle radius, calculated from the results of Beard and Grover using a particle density of 5.67 gm/cc at $a \gtrsim 1$ m.

Beard (1974), similarily, presents collision efficiency versus Stokes number for the scavenging of submicron particles by small raindrops for drop Reynolds numbers of 20, 100, 200 and 400. His results account for collision geometry in terms of particle density as well as account for low-order inertia effects of the submicron particles. Beard states, "that the density of the larger particles, where $N_{Stk} \gtrsim 0.05$, is an important consideration since it determines the particle size and consequently it affects the collision geometry. This is true only for a grazing trajectory when the particle collides on the forward side of the drop. For smaller particles, where $N_{Stk}<0.05$, the density is unimportant because of wake capture. In the rear flow area these nearly inertialess particles move toward the drop under the influence of gravity and with the help of the recirculatory wake for $N_{Re}>20$." Beard presents collision efficiencies for particle densities of 1, 4 and ∞gm/cc at constant Reynolds and Stokes number. We interpolate the collision efficiencies for AgI particles from a plot of collision efficiency versus $\rho_a^{-1/2}$. We justify this approximate functional dependence on $\rho_a^{-1/2}$ as follows. The interception collision efficiency, E_I, given by Eq. (12) yields values that are approximately proportional to p, and thus a, for Reynolds numbers as low as 20. For constant N_{Stk}, a is proportional to $\rho_a^{-1/2}$. Thus, the collision efficiencies presented by Beard are collision geometry related for $N_{Stk} \gtrsim 0.05$ and have an approximate functional dependence on $\rho_a^{-1/2}$ at constant Reynolds and Stokes number. These extrapolated values for AgI particles usually differ little from the values at $\rho_a = 4$. The collision efficiencies are plotted in Figs. 3c through 3f where the increase in collision efficiency can be observed due to the wake effect for particle radii less than 0.27 μm ($N_{Stk}< 0.05$).

In Figs. 3g and 3h for N_{Re}= 600 and 895, collision efficiency was obtained due to interpolation between N_{Re} = 400 (Beard and Grover, 1974) and potential flow (Fonda and Herne, 1957) for forward side capture. No wake capture is shown in these plots since wake shedding occurs for $N_{Re} \gtrsim 450$ (Moller, 1938). This discontinuance of wake capture is discussed by Beard (1974) in terms of experimental data.

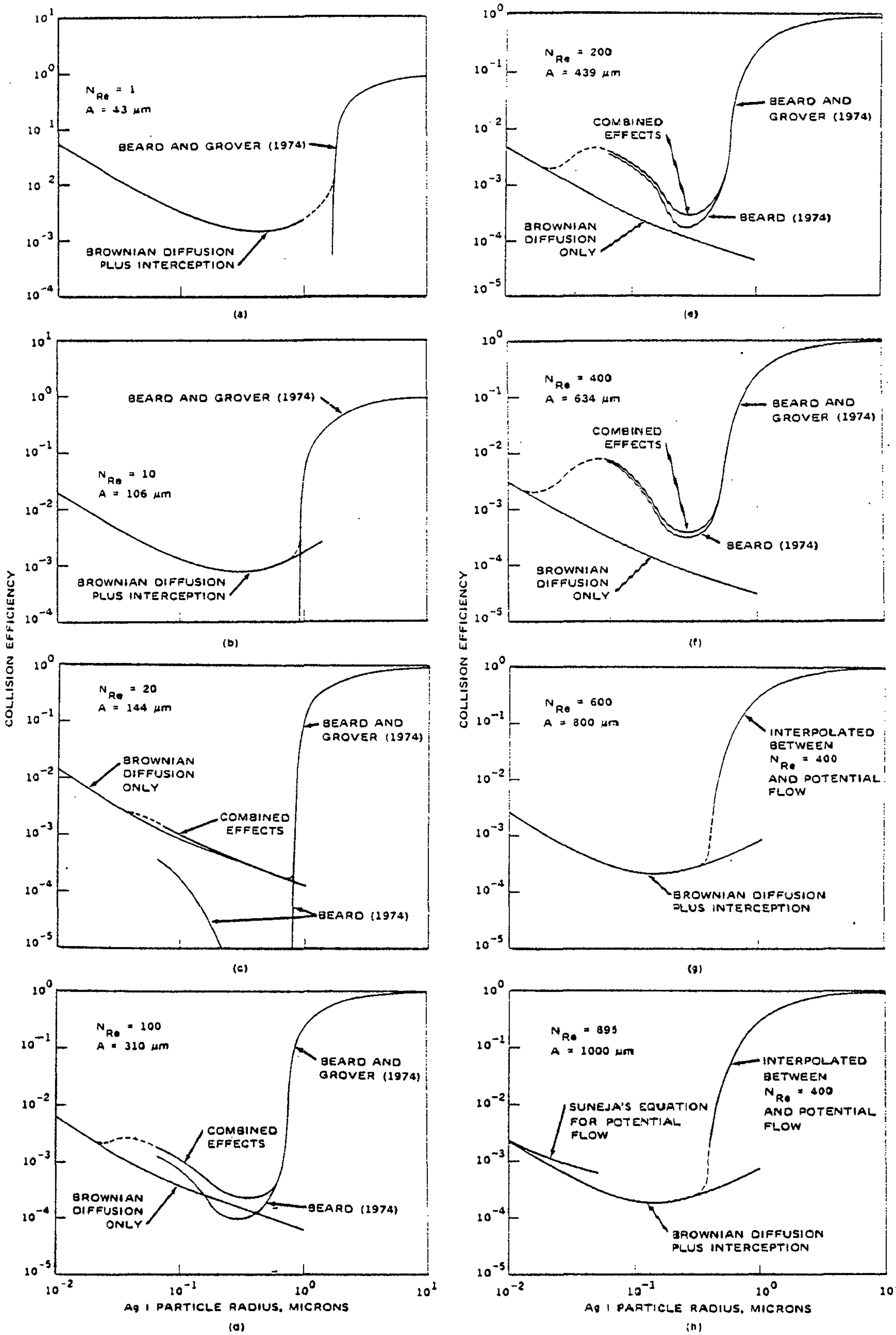

FIGURE 3. Collision efficiency versus AgI particle radius, ranging from 0.01 to 10 μm, for drop Reynolds numbers of (a) $N_{Re}=1$, (b) $N_{Re}=10$, (c) $N_{Re}=20$, (d) $N_{Re}=100$, (e) $N_{Re}=200$, (f) $N_{Re}=400$, (g) $N_{Re}=600$ and (h) $N_{Re}=895$.

c. Combined Collision Efficiencies for $N_{Re} \gtrsim 1$.

In Figs. 3c through 3f, collision efficiencies for Brownian diffusion only, values of which were transferred from Fig. 1, are shown for a $\lesssim$ 1 μm. From the results of Beard (1974) and from those for Brownian diffusion only, combined collision efficiencies are obtained and shown in Figs. 3c through 3f. Actually, these efficiencies are not quite additive at particle sizes where wake capture predominates, but for practical purposes, these values are adequate. Beard does not give collision efficiencies for a<0.07 m. Presumably, the smaller particles do not have sufficient inertia to penetrate the wake envelope. However, this cessation of wake capture is likely not to be discontinuous, and we approximate a continuous transition by a dashed curve between the Brownian diffusion only and combined effects curves for a <0.07 m.

In Figs. 3a, 3b, 3g and 3h for Reynolds numbers of 1, 10, 600 and 895, collision efficiencies for Brownian diffusion plus interception are shown for a $\lesssim$1 m. These values of collision efficiency were transferred from Fig. 2. The equivalent of interception was included in Figs. 3c through 3f by means of Beard's results. In Figs. 3a, 3b, 3g and 3h, these collision efficiencies for Brownian diffusion plus interception are joined by a short dashed curve to the limiting values of collision efficiency of Beard and Grover or of those interpolated between N_{Re}=400 and potential flow. This dashed curve approximates continuity between particles having interception and Brownian diffusion and those having inertial impaction as the capture mechanisms.

d. Collision Efficiences for $N_{Re} < 1$.

Plots of collision efficiency versus droplet or particle radius are shown in Fig. 4 for drops falling with viscous flow. Collision efficiency values for a $\leq$1 μm are transferred from Fig. 2. Collision efficiency values for a >1 μm are the results of Klett and Davis (1973) for collector drops having radii of 10 μm and 20 μm (see Figs. 4b and 4c). Collision efficiencies for 10 and 20 μm water drops capturing AgI particles having radii larger than 4 and 8 μm, respectively, are from the results of Klett and Davis even though the drops are overtaken by the particles.

COLLECTION KERNELS

The collision efficiencies of Figs. 3a through 3h and Fig. 4 are used in Eq. (1), assuming a coalescence efficiency of one, to calculate collection kernels. These collection kernels are shown as parameterized curves in Fig. 5 for water drops, having radii ranging from 5 to 1000 μm, capturing AgI particles, having radii ranging from 0.01 to 10 μm.

We have assumed for the present time that coalescence efficiency is unity because most collection kernels, especially those of practical concern, considered here are for small radius ratios. Coalescence efficiency has been shown to be close to unity for radius ratios less

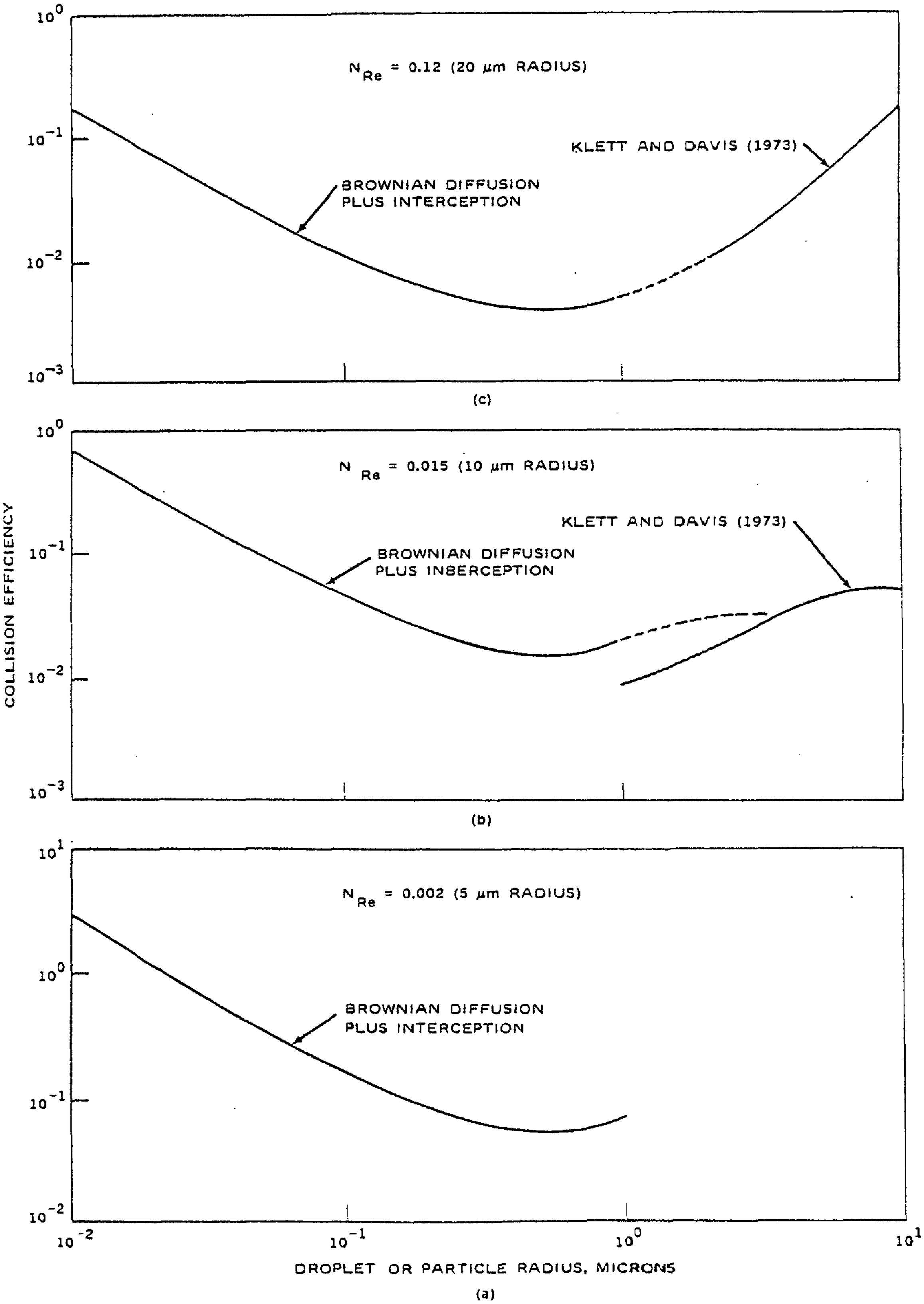

FIGURE 4. Collision efficiency versus droplet or particle radius, ranging from 0.01 to 10 μm, for viscous flow at (a) N_{Re}=0.002, (b) N_{Re}=.015 and (c) N_{Re}=0.12.

than 0.1 (see, e.g., Levin, 1973) in the case of water drops interacting with water droplets. Also, silver iodide nuclei probably have higher coalescence efficiencies because of their rough surfaces. Adjustment of these values of collection kernel, especially for the large silver iodide nuclei with radius ratios greater than 0.1, will have to await experimental determination.

Velocities of the drops and micron-size nuclei used in Equation (1) are found at 800 mb and -2°C by means of Stokes law and the standard drag curve with the assumption that they are spheres having smooth surfaces. For $N_{Re} < 0.1$, velocity of a sphere is

$$V_S = 2 \rho_S g S^2 / 9 \mu \tag{13}$$

where ρ_S = sphere density

S = sphere radius

For $N_{Re} > 0.1$, the procedure of calculating terminal velocity as given by Mason (1971) was used.

Collection kernels using the collision efficiencies of Klett and Davis are shown as dashed curves in the lower right hand corner Fig. 5 because of the uncertainty of applying their results to the water drop-AgI particle hydrodynamic interaction. In all probability, the kernels in Fig. 5 are minimum values for micron-size AgI nuclei interacting with 50μ m or smaller water drops; however, care should be exercised in using these particular collection kernels since coalescence efficiency was assumed to be unity for these radius ratios of order 0.1 and larger.

The K=0 line in the lower right hand corner of Fig. 5 represents the case where the AgI particle and water drop terminal velocities are equal. The K=0 line is not shown for water drops having radii larger than 15μ m since inertial effects cause the velocity difference between the particles and drops to be finite. Even though the particles and drops are of unequal size, the assumption of a non-zero velocity difference is based on the theoretical and experimental results of Klett and Davis (1973) and Steinberger (1968), respectively, that for pairs of equal spheres falling along their line of centers a significant acceleration effect occurs for Reynolds numbers as small as 0.03, corresponding to water droplet radii of 15 μm.

The horizontal discontinuity line, at a water drop radius of 658 μm (i.e., $N_{Re} = 450$), in the upper left hand corner of Fig. 5 signifies the abrupt transition from a regime having wake capture as a significant capture mechanism for AgI particles with radii ranging from 0.02 to 0.3 μm (below line) to one having only Brownian diffusion plus interception as the capture mechanism (above line). As mentioned previously, wake shedding, and thus no wake capture, occurs for drop Reynolds numbers equal to or greater than 450.

Also, the collection kernels for water drops capturing water droplets or particles having densities of 1 gm/cm^3 are shown in Fig. 6.

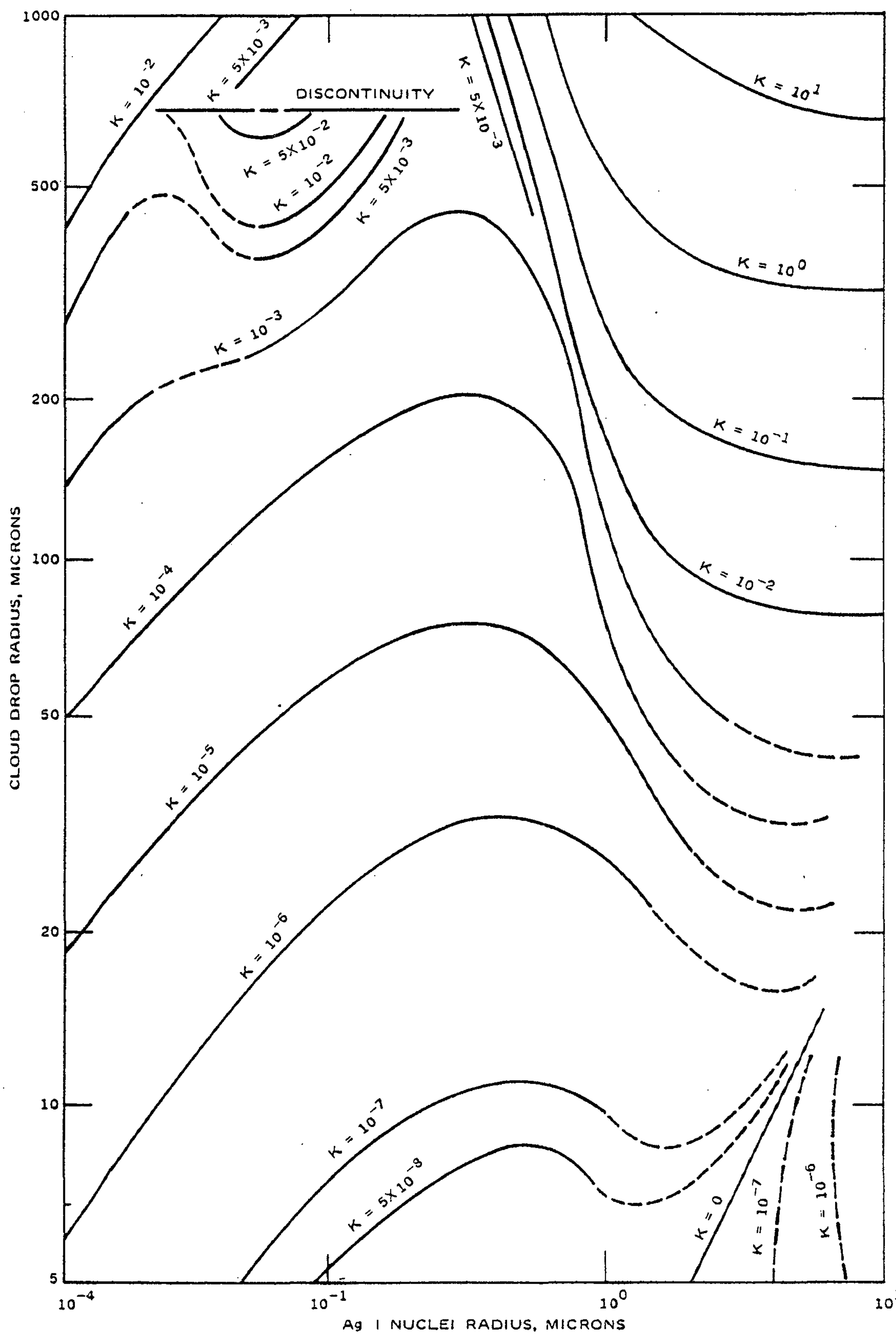

FIGURE 5. Collection kernels expressed as parameterized curves for cloud drop radius ranging from 5 to 1000 μm and AgI nuclei radius ranging from 0.01 to 10 μm, at -2°C and 800 mb.

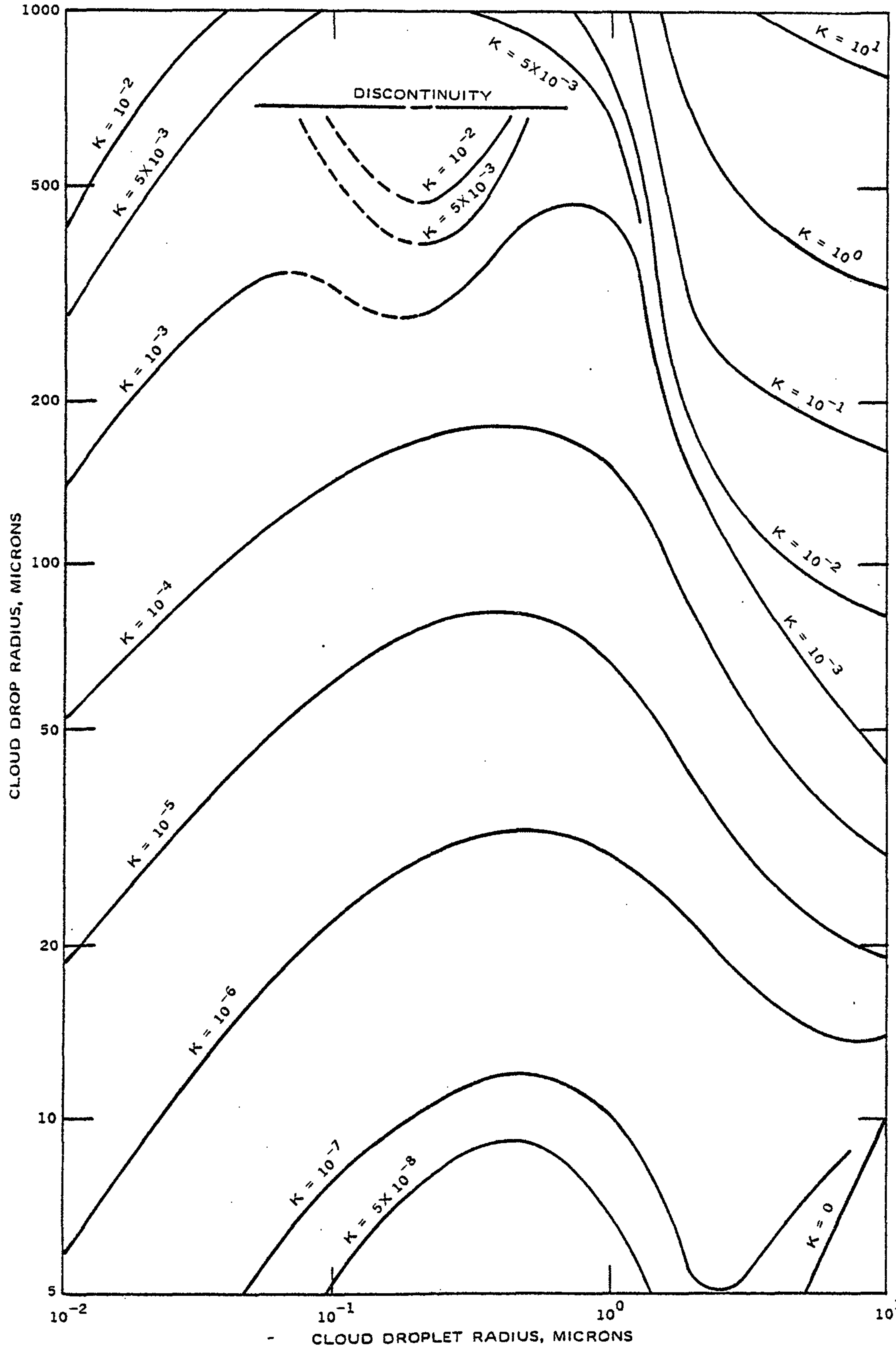

FIGURE 6. Collection kernels expressed as parameterized curves for cloud drop radius ranging from 5 to 1000 μm and cloud droplet radius ranging from 0.01 to 10 μm, at -2°C and 800 mb.

These kernels were obtained, assuming a coalescence efficiency of one, by using collision efficiencies similar to those in Figs. 3a through 3h for a particle or droplet density of 1 gm/cm^3 and those of Fig. 4. Similarily, a horizontal discontinuity line at the upper portion ofFig. 6 signifies the abrupt transition in capture mechanism at N_{Re} = 450 for droplets or particles having radii ranging from 0.05 to 0.7 μm.

In both Figs. 5 and 6, dashed curves are shown below the discontinuity lines to signify a continuous transition from Brownian diffusion to significant wake capture with increasing particle size for water drops having Reynolds numbers less than 450.

The collection kernels of Figs. 5 and 6 usually can be used with the assumption that these are minimum values. The applicability will be discussed in the next two sections where the effects of turbulence, thermophoresis, diffusiophoresis, and electrophoresis on collection kernel are discussed.

OTHER MICROPHYSICAL PROCESSES AFFECTING THE COLLECTION KERNELS

a. Turbulence. The effect of small-scale turbulent fluid motions on the collisional trajectories of cloud drops has recently been studied by Almeida (1974). Collision efficiencies were calculated for ε, the rate of dissipation of turbulent energy per gram of medium, being equal to 1 and 10 cm^2/sec^3. These values of ε are for weak convection in cumulus clouds, in fact, ε = 1 cm^2/sec^3 represents an appropriate level for the state of cloud development (Almeida, 1974). The effects on collision efficiency for large drops (A> 40 μm) was found to be insignificant while for the interaction of small droplets (5<A<25 μm), collision efficiency increased significantly. In fact, for the drop and droplet pair having radii of 15 and 6 microns, a two orders of magnitude increase was found when going from the non-turbulent (ε=0) to the turbulent case, ε=1 cm^2/sec^3. The increase in collision efficiency when going from the non-turbulent case to ε=1 cm^2/sec^3 was much greater than that for the increase in turbulence level from ε=1 to 10 cm^2/sec^3. If these data are correct, turbulence during the early stages of cloud development could increase the collection kernels for the capture of micron-size particles by up to two orders of magnitude, possibly more in the case the capture of AgI nuclei due to their greater inertia over that of the equivalent size water droplets.

One might hypothesize that capture of submicron particles by drops may be increased by turbulent diffusion. Actually, it is doubtful that turbulence would increase diffusion of submicron particles to a drop since the turbulent eddies would be damped out substantially in the viscous boundary layer. This opinion has been expressed, also, by Slinn (1974). In fact, Freidlander and Johnstone (1957) measured deposition of aerosol in turbulent flow through tubes. No deposition of aerosol (a $\simeq$ 0.4 μm) occurred at tube Reynolds numbers of 12,600 and 14,900 until the boundary layer in the tube became turbulent downstream. Turbulence in the boundary layer of a drop does not occur until a drop Reynolds number of 3x10^5, much larger than those of cloud drops. Thus, we conclude that turbulence will increase the collection kernels shown in Figs. 5 and 6, for drops having $A<40$ μm interacting with particles having $a>1$ μm with no effect when $A>40$ μm or $a<1$ μm.

b. Diffusionphoresis and thermophoresis. Slinn and Hales (1971) showed that the thermophoretic number flux was greater than the diffusiophoretic number flux of particles, i.e., for an evaporating drop, the result is that of increased collisions with submicron particles; for condensation on a drop, collisions are retarded. To obtain their results, it was assumed that the drops had reached a steady-state temperature distribution. Vitorri (1973) stated that this assumption is not valid in the atmosphere since the temperature field will be distrubed significantly by convenction as well as the mass flow of water vapor. Recently, Slinn (1974), also, has indicated that the calculations of Slinn and Hales (1971) are not necessarily valid for the realistic case of unsteady-state.

A quantitative calculation of the effects of thermo-and diffusiophoresis on collision efficiency would be very difficult for the unsteady-state case. Probably, a well defined laboratory experiment is needed to study these phoretic effects on collision efficiency; however for now, we tend to support the premise, based on Vittori's paper, that diffusiophoresis is controlling even for submicron particles being captured by drops. Moreover, recent calculations by Pilat and Prem (1976), although for a steady-state temperature distribution, show that the diffusiophoretic force exceeds the thermophoretic force on a particle. Although they assume a potential flow field around a water drop having a 50 μm radius, their collision efficiencies are increased by up to 2 orders of magnitude for particle radii 0.01 to 1 μm if a drop is 5°C cooler than the surrounding saturated air.

c. Electrophoresis. Electrophoresis is the tendency of particles or droplets to move under the influence of electrically produced forces. The electrophoretic capture of small droplets or aerosol particles by drops has been addressed by Cochet (1952), Levin (1954, Friedlander (1967) and Zebel (1968), and recently by Parker (1974), Grover and Beard (1975) and Schlamp, *et al*. (1976).

The calculations by Parker for potential and viscous flow around charged drops indicate that significant increases in collision efficiency can occur even for weakly charged particles; however, the drop charges used in his calculations were abnormally high, i.e., a drop charge, Q_A, of 0.06 esu on a 200 μm radius drop or over 2 orders of magnitude greater than the mean drop charge for thunderstorms according to the results of Takahashi (1973).

Grover and Beard (1975) and Schlamp, *et al*. (1976) using the stream function fields given by Le Clair *et al*. (1970) calculated collision efficiencies for electrical effects that might exist during thunderstorm and pre-thunderstorm conditions.

For drops with $A \gtrsim 70$ m capturing droplets with $a \geq 1$ μm, Schlamp *et al*. found that the effect of electric fields and drop charges on collision efficiency is negligible even though the field strengths and drop charges are as large as those found in thunderstorms. For smaller collector drops, they found that external electric fields of 500 volts per cm and larger significantly increase collision efficiencies; however, these are strong fields compared to those of 10 to 100 volts per cm found in cumulus clouds. Hocking and Jonas (1970) found negligible effects on collision efficiency for fields less than 100 volts per cm. For collector drops less than 40 μm radius, the results of Schlamp et al. show that the collision efficiency of two interacting drops of opposite charge is significantly increased over those efficiencies given by Klett and Davis (1973) for neutral drops if the magnitude of the charges are equivalent to the mean values found in thunderstorms, i.e., $|Q_A| = 2A^2$, where Q_A is expressed in esu and A in cm. For drop charges comparable to those found in warm clouds, i.e., for $|Q_A| = 0.2A^2$ (see Takahashi, 1973), the collision efficiencies are no more than a factor of two greater than the neutral drop results of Klett and Davis.

Grover and Beard (1975) calculated collision efficiencies for charged particles having radii from 0.2 to 10 μm and densities from 1 to 4 gm/cc interacting with charged drops having radii from 42 to 433 m. The electrical charges on the particles were $|Q_a| \leq 20a^2$ where Q_a is expressed in esu and a in cm. Whitby and Lui (1966) calculated the charge versus size distribution for particles between 0.01 and 1.0 μm in diameter in equilibrium with a bipolar ion atmosphere. The charge, $|Q_a| = 20a^2$ is about 40 times larger than this bipolar ion equilibrium level charge and is about 1/5 of the charge on a perfectly spherical particle of radius, a, that induces corona breakdown of the atmosphere.

Upon examination of the data of Grover and Beard, we find their collision efficiencies never exceed our values for electrical neutrality by more than a factor of 10 for drops with $|Q_A| \leq 0.2A^2$ and oppositely charged submicron particles with $|Q_a| \leq 20a^2$. However, if the drops have the mean value of charge associated with thunderstorms, i.e., $|Q_A| = 2A^2$, then the collision efficiencies for charged submicron particles interacting with the oppositely charged drops are up to two orders of magnitude greater than our values. There is only about an 8 fold increase in collision efficiency for micron-size particle interacting with the highly charged drops having A<40 μm; however, for larger drops interacting with micron-size particles the effect on collision efficiency is insignificant.

No values of electrical charge are available for AgI nuclei; however, the charge of nuclei produced by pyrotechnics is positive due to the pyrolytic stripping of electons. If there is any interest in seeding clouds that have significant electrical activity, measurements of AgI aerosol electrical charge should be made because of the possibility of large charges existing on the nuclei and thus large collision efficiencies.

In summing up this section, if experimental values of electrical charge on AgI nuclei are found to be large, e.g., $2a^2 < Q_a \leq 2\text{-}a^2$, then the collection kernels in Fig. 5 should definitely be used as minimum values when seeding that portion of a electrically active cloud where negatively charged drops predominate. Conversely, the kernels of Fig. 5 may be too large if one is seeding that portion of a cloud where positively charged drops predominate. Exception to the last two statements is expressed for the kernels where $a \gtrsim 1$ μm and $A \gtrsim 70$ μm being that they are little effected even when $|Q_A| \leq 20A^2$ and $Q \leq 20a^2$. Also, for drops having charges that we might normally find in seedable cumulus clouds, i.e., $|Q_A| \leq 0.2A^2$, the collection kernels are increased by no more than a factor of 10 for submicron particles having $Q_a \leq 20a^2$.

5. APPLICABILITY OF COLLECTION KERNELS TO CLOUD SEEDING

The collection kernels of Fig. 5 can be applied as minimal values when seeding in a cloud where condensation is occurring and where negatively charged droplets predominate. Webb and Gunn (1955), Pudovkina and Katsyka (1960), Magono and Kikuchi (1961), Petrov (1961), Makhotkin and Solov'ev (1965) and Colgate and Romero (1970) have found a predominance of negatively charged drops in clouds. Also Sergieva (1959) found more negatively charged droplets in the developing stages of the cloud. In a later study, Takahashi (1972) has found that "negatively charged droplets predominate at the lower part of a cloud, and positively charged droplets predominate at the upper part of the cloud". Therefore, one should inject nuclei as low as possible in the cloud, according to the nucleation tempeature of the nuclei employed, and in the updraft. Otherwise, much smaller values of collection kernel than those shown in Fig. 5 may be applicable to seeding elsewhere in the cloud.

In Fig. 5, the collection kernels are greater than 10^{-6} cm^3 sec^{-1} for the capture of 0.01 to 10.0 μm radius AgI nuclei by cloud drops with radii 40 μm or greater. These kernels are large enough to bring practical concentrations of nuclei into contact with cloud drops at a rate such as to promote rapid freezing of cloud water with a large heat release, as in the case of seeding an updraft of a cumulus cloud. The updraft in a developing cumulus cloud has a much larger liquid water content, thus, larger drops exist than in downdrafts. Also, Zaitsev (1950) has found that droplets are smaller at a periphery of the cloud than in the center. Droplets of the order of 200 μm radius will remain suspended in updrafts of about 5 ft/sec (1.5/sec), and even larger drops, up to 1000 μm radius, are frequently observed striking aircraft windshields in higher updrafts. No really good measurements are available from updraft cores, but the drop sizes are definitely larger there. Liquid water commonly ranges between 1.5 and 3.5 gm/m^3, occasionally rising as high as 5 gm/m^3, in tropical clouds of the type we have encountered in the Philippines. According to our collection kernels of Fig. 5, only a few hundred to a few thousand nuclei per cm^3 are necessary to cause nucleation of almost all the drops with $A \gtrsim 200$ μm within one second.

Let us assume a hypothetical case of AgI nuclei having radii of about 0.1 m being distributed at a concentration of 5×10^3 cm^{-3} in an updraft in which most of the liquid water is contained in water drops having radii of about 200 μm. The collection kernel is about 2×10^{-4} cm^3 sec^{-1} which is sufficient for each drop to encounter one AgI nucleus in about one second.

If about 200 μm radius drop existed in each 10 cubic centimeter of cloud (i.e. liquid water content of 3.4 grams/m^3), then about 271 calories per cubic meter of heat would be released in about one second. This initial heat release would be followed by a much greater heat release within a few minutes caused by condensation as moist air passes relatively fast by the frozen drops.

However, in the downdrafts of the outlying portions of a cloud, drops are generally of the order of 15 μm radius with a liquid water content less than 0.4 grams per cubic meter. The collection kernel from Fig. 5 is about 5×10^{-7} cm^3 sec^{-1} for contact of 0.1 μm radius AgI nuclei with 15 μm radius drops. This is equivalent to using a nuclei concentration of 2×10^6 cm^{-3} in order that each drop encounter one AgI nucleus in the same order of time as in the case of drops having 200 μm radii with much less heat of fusion release. However, if the droplets are positively charged and the rate of evaporation is significant, which is highly probable in a downdraft, then even much larger concentrations of nuclei would have to be injected. Also, condensation would be much smaller because of the moist air passing slowly by these frozen droplets with very small terminal velocities.

6. CONCLUSIONS

Hence a cumulus cloud should be seeded only in the updraft because practical concentrations of nuclei can be used while significant changes of buoyancy will occur from the substantial heat release. Seeding the downdraft requires unreasonable concentrations of nuclei while the heat release, even though smaller than that for the updraft, may very well disturb the delicate balance of circulation within the cloud. The collection kernels given in Fig. 5 will permit modeling of the glaciation process such that decisions as to when, where, and how much to seed, can be determined with perhaps some insight being developed into determining the change in air circulation brought about by seeding.

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