Clouds and precipitation

J. Doyne Sartor

Citation: Physics Today **25**, 10, 32 (1972); doi: 10.1063/1.3071045
View online: https://doi.org/10.1063/1.3071045
View Table of Contents: http://physicstoday.scitation.org/toc/pto/25/10
Published by the American Institute of Physics

Clouds and precipitation

Theoretical models, laboratory experiments and flights by an instrumented sailplane all combine to improve our knowledge of the physical conditions inside clouds.

J. Doyne Sartor

In these days of emphasis on environmental problems, studies of clouds and precipitation take on an added importance. Clouds and precipitation cleanse the atmosphere of natural and man-made pollutants or process them for later removal. Cloud radiative and dynamic properties control a good deal more than half of the solar energy available for keeping the atmosphere moving, and precipitation keeps the continents green (or white). Destructive storms are spawned mostly from cloud systems, but Man can modify his local environment to some extent now through the "seeding" of clouds, and possibly he will eventually be able to control severe storms and remove damaging pollutants.

The formation of clouds in the atmosphere is a consequence of the diffusion of water vapor onto suspended particles when moist air is cooled to slightly better than 100% saturation by adiabatic expansion. Studies of the physics of this process, and of the subsequent history of the cloud components, are advancing on three fronts—theoretical calculations, measurements on laboratory models, and *in situ* measurements in clouds. Some of the theoretical work and laboratory studies were mentioned in my earlier article for PHYSICS TODAY,[1] particularly for the case where electric fields exist in the cloud. New since then are our efforts at the National Center for Atmospheric Research to make measurements relevant to cloud microphysics within the cloud itself (figure 1) instead of only in laboratory simulations. At the same time the laboratory models have been improved with the design and construction of a "particle control chamber" in which many of the relevant processes can be studied at will.

We feel that we have stepped over the threshold in our laboratory and field experimental techniques, so that many of the crucial experiments in the physical processes of natural clouds are now possible. They will require considerable time to complete, if only because of their complexity and number. The theoretical models are already very complex and quite sophisticated mathematically, but we have lacked detailed data for their experimental verification. The models are usually designed to consider, on the microphysical scale, only a "homogeneously" random distribution of particles that does not vary with position except by the processes controlled by the model; our research shows that the data are inhomogeneous, but how significant the deviations are we do not yet know. The immediate problem is to learn how to use the models to evaluate these spatial and temporal inhomogeneities in the observed data. Many of the physical processes involved in the formation of clouds and the growth of precipitation are known acceptably well and can be measured with adequate precision; however, the manner in which these and other less well defined processes interact is not quantitatively well understood.

In the free atmosphere, adiabatic expansion results from the lifting of the air by its movement over terrain of increasing height, over air of greater density, in response to the larger scale circulation, or as the consequence of thermodynamic instability. Lifting is specified by the evaluation of meteorological observations or by direct measurement, or by forecasts of the circulation and thermal structure of the atmosphere.

Calculations of the formation of precipitation from clouds containing the rising air require a quantitative understanding of the nucleating properties of the particulates, the rates of diffusion of water vapor relative to cloud droplets and ice crystals, and the accretion rates of distributions of cloud droplets and ice particles. The calculations of these complicated and interactive processes contain complex tradeoffs involving many physical processes acting partly in a deterministic way and partly in a probabilistic or stochastic way on space, time and force scales varying over many orders of magnitude.

Studies of the motions of the air in clouds and the dynamical processes that are involved in their creation, growth and dissipation are extremely complex also. A fully three-dimensional mathematical model of a convective cloud, including interactions of the microphysics

---

J. Doyne Sartor is Head of the Atmospheric Physics Department and a program scientist in Cloud Physics at the National Center for Atmospheric Research, Boulder.

Explorer sailplane flying above mountain-wave cloud at an altitude of 4.7 km near Boulder, Colorado, piloted by Wim Toutenhoofd. (Photo: Robert Bumpas, NCAR.) Figure 1

with the air motion, would exceed the storage capacity and real-time computation capability of the largest computers planned for the immediate future. One- and two-dimensional models are used now, and all are somewhat artificial in their specifications of cloud-cell geometry and the incorporation of empirical parameters relating vertical motion to cloud buoyancy and scale.

Mathematical models of cloud dynamics and microphysics are most useful at the present time as explicit expressions of a set of complex hypotheses that provide useful guides to what might otherwise be almost hopelessly disoriented observational programs.

The discovery by Vincent Schaefer[2] that a vast number of ice crystals could be formed by nucleating supercooled droplets in the atmosphere (by dropping dry ice into clouds with air temperatures less than 0 deg C) sparked a considerable amount of interest in *cloud microphysical processes.* By this last term I mean the nucleation of droplets and ice crystals and their growth by diffusion, the coalescence and accretion of cloud particles, and the fallout and evaporation of precipitation and the resultant contribution to the dissipation of clouds. This interest increased when, shortly afterward, Bernard Vonnegut[3] found that the longer-lasting, more easily dispensed, silver-iodide crystals would act similarly.

Studies of cloud microphysics require calculation and observation of the vertical motion of the air, especially in the core of convective clouds. The core updraft, and the resulting dry and then moist adiabatic expansion of the air, controls most of the dynamic behavior of convective clouds and the resulting precipitation growth. Convective clouds are responsible for most heavy precipitation, all hail, all tornadoes and most or all cloud-to-ground lightning.

Nucleation of the cloud droplets occurs first on particulate matter at supersaturations slightly exceeding 100%. Freezing occurs naturally on suitable nuclei whose activation is a probability function that varies with temperature and size. Once a cloud droplet or ice crystal is nucleated, the problem is initially one of the diffusion of water vapor to each of the cloud elements, which at low temperatures is greatly different for supercooled drops and ice crystals. Later the collision coalescence and accretion growth of cloud particles is superimposed on the diffusional growth.

The equations of cloud microphysics can be formulated as follows:

$$(n_i)_k = \mathbf{S}_t \mathrm{T}_k \{-\nabla\cdot[n_i(\mathbf{u}-\mathbf{v}_i)]_k + \mathrm{H}_k + \mathrm{I}_k + \mathrm{J}_k\}\,\delta t \quad (1)$$

Here n_i is the number density; subscript i denotes size of particle and subscript k indicates cloud-particle type. For aerosols, $k = 1$, for liquid drops, $k = 2$ and for ice particles $k = 3$. The large **S** denotes a general integration or summation, here over time t. The transfer function T_k specifies the rate at which particles change character or type—from aerosols to drops to ice, or the reverse, in a rising parcel of cloud air. T_k varies with the temperature of the air, the temperature of the particle, the humidity of the air, and the nucleation properties of the aerosols and cloud drops. The air velocity and particle velocity are shown by $\mathbf{u}$ and $\mathbf{v}_i$ respectively. The first term in the curly brackets represents particle transport and sedimentation. The function H_k expresses the stochastic growth of particles by collision, coalescence and accretion; I_k expresses the breakup of cloud drops or ice crystals that have become too large to sustain further collisions or accretions, and J_k represents change in size by water-vapor diffusion.

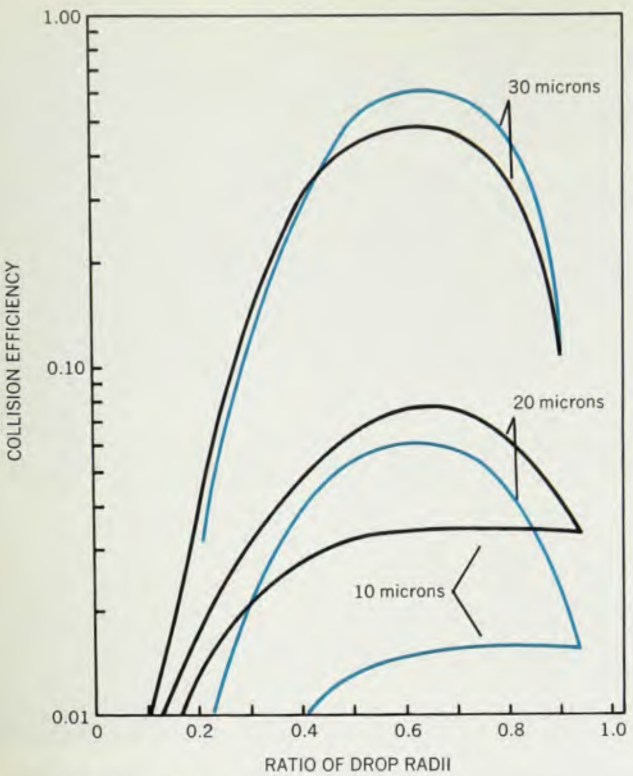
The relative change in the total number of particles of a given type for the accretion and coalescence function H_k is:

$$d/dt\,(n_i)_k = \mathrm{H}_k = \tfrac{1}{2}\,\mathbf{S}_j \mathrm{R}_k\cdot n_j n_{i-j}\delta r_j \delta r_i - n_i \mathbf{S}_j \mathrm{R}_k\cdot n_j \delta r_j \delta r_i \quad (2)$$

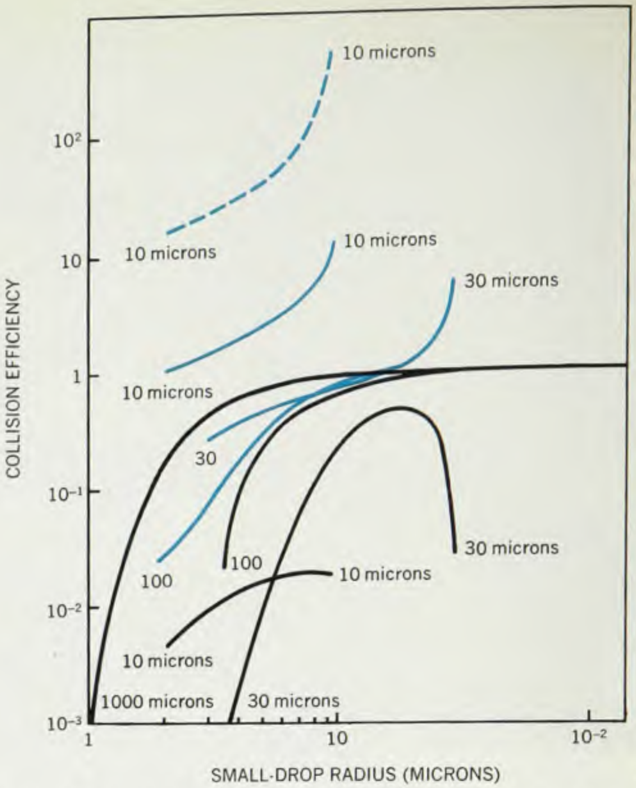
where

$$\mathrm{R}_{k=2\,(\mathrm{water})} = \pi(r_j + r_{i-j})^2\,|\,\mathbf{v}_j - \mathbf{v}_{i-j}\,|\cdot E_c E_a$$

Here E_a and E_c are accretion and collision efficiencies respectively, and subscripts i and j denote size intervals. Particle radius is shown by r_j, r_{i-j}, and $\mathbf{v}_j$, $\mathbf{v}_{i-j}$ are velocities of uncharged particles. As in equation 1, the large **S** indicates a general integration or summation process that depends on the nature of the data. R_2 is generally called the "collision kernel" and contains



Collision probability for cloud droplets. Calculations by Milford H. Davis (black lines), who used slow-flow corrections, are compared with those using a prescribed minimum separation between droplets (colored lines). The curve labels show large-drop radius in microns. (From M. H. Davis, reference 8.) Figure 2



Effect of electrostatic forces on collision probability. Black lines are for zero field, zero charge on the drops. Solid color is for a field of 10 esu, zero charge. Dotted color is for zero field and a charge of $-10r_1^2$ on the large drop, $+10r_2^2$ on the small drop. Curve labels show large-drop radius in microns. Figure 3

the product of the geometrical collision cross section $\pi(r_j + r_{i-j})^2$, the relative vertical velocities $|\mathbf{v}_j - \mathbf{v}_{i-j}|$, the collision frequency E_c and the accretion efficiency or probability E_a.

A great deal of effort[4-8] has gone into obtaining the collision efficiency E_c, which varies greatly in the small cloud-droplet range between a few microns and 50 microns radius.

The airflow about the cloud droplets in the size range below 40 to 50 microns radius is dominated by viscous forces. Calculations of the drag force on two drops in close proximity are obtained by Stokes's and Oseen's steady-state flow approximations with bi-spherical geometry, to obtain the two-body drag force on each drop. The drag forces are obtained for any possible drop radius ratio and axisymmetrical orientation. The drag force, together with the force of gravity and the two-body electrostatic forces obtained in bi-spherical geometry also, is introduced at each integration step into an equation of motion for freely moving droplets to obtain numerically the probability of collision between two drops, initially separated at large distances apart, by a prescribed horizontal offset. The two-body solutions were first given by Leslie M. Hocking[5] using the Stokes approximation, but his results were in error due to a premature truncation of the series expressing the drag forces. This truncation error was corrected by Milford H. Davis and myself[7] to give the collision probability (collision efficiency). These calculations were checked later by Hocking and Peter Jonas[9] and found to be in essential agreement if a collision is defined arbitrarily to occur when the drop surfaces reach a separation of 10^{-3} of the large-drop radius. Davis[8] has eliminated the artificial surface separation cutoff by considering the slip flow of the kinetic theory of gases to apply when the droplets approach each other very closely. The Hocking and Jonas–Davis and Sartor calculations are shown by Davis as the colored lines in figure 2. His own results are the black lines.

Above 50 microns radius, the larger drop collides with 70 to 90% of the smaller drops in its path, except for much smaller drops when the probability drops off rapidly with size. As the larger drop grows, the probability of collisions with smaller drops moves closer to 100%, except when the smaller drop is less than 10 microns.

In the electrical environment of a thunderstorm or other highly electrified storms, the collision efficiency E_c and the relative vertical velocities, $\mathbf{v}_j - \mathbf{v}_{i-j}$ are both strongly affected, especially for drops less than 30 microns radius. A summary of calculations of collision efficiencies that I made[10] using the two-body electrostatic force computations of Davis[11] is shown in figure 3. The collision efficiencies of drops smaller than 30 microns are the most strongly affected by the addition of the electrostatic two-body forces. The field of 10 esu (3000 v cm^{-1}), although high, can be expected at some place in all thunderstorms.

Relatively little is known (or has been proven at least) about the coalescence or accretion efficiency, E_a, except that theoretically it is anticipated to be near unity for the smaller drops, charged drops and drops in an electrical field, and that it decreases for the larger drizzle drops and raindrops.

Measurements within clouds

What weather conditions should we have, and what measurements should we make, if we are to attempt to observe these microphysical processes as they occur—in the cloud?

The larger-scale circulation usually depicted on weather charts at several levels in the atmosphere must be favorable for the development of rising parcels of air; at least the circulation must not be strongly unfavorable. Excluding orographic flow and instability conditions of the atmosphere, the circulation is most favorable for vertical motion and free convection when convergence in the lower layers is topped by divergence in

Table 1. Instrumentation of the Explorer sailplane

Instrument	Range*	Accuracy	Sampling volume and/or time resolution
Camera: in-situ particles, liquid and solid	For concentrations, ≥ 1.5 microns For sizing, ≥ 8 microns	±20%	5.0 cm^3 for 10-micron droplet, 130 cm^3 for ice; 0.5 sec
Electrostatic cloud droplet disdrometer	4 to 22 microns in 1.5-micron intervals†	±10%	1.0 cm^3 per 0.5 sec
Cloud droplet impactor slides	≥ 2 microns	±15%	50 cm^3, occasional sample
Variometer: vertical speed of sailplane	-40 to $+40$ m/sec	±0.4 m/sec	< 0.5 sec
Pressure altitude	1010 to 120 mb	±0.5 mb	< 1 sec (0.5-mb pressure altitude resolution obtained by integrating vertical speed from variometer)
Temperature	-75 to $+30$ deg C	unknown	to be determined after computerized analysis
Indicated airspeed	0–67 m/sec	±4 m/sec	<0.5 sec
Vertical accelerometer	-10 to $+10$ g	±0.3 g	<0.5 sec
Lyman-alpha humidiometer	-40 to $+20$ deg C	±2 deg C	<0.1 sec

---

** Particle-size dimensions are radii*

† All droplets with radii greater than 22 microns are counted in one channel

the same column at higher levels and there is advection of warm air into the lower layers of cold air at higher levels or both.

Once launched into a favorable circulation environment, a cloud develops buoyancy and accelerated vertical motions through the release of the latent heat of condensation and freezing. The nucleation properties of the aerosol moving into the cloud need to be observed in the air before it enters the cloud. We must observe the initial and continuing droplet spectra with as fast a time resolution as possible, and we require observations of the onset of ice and the relative concentrations of ice particles and supercooled cloud droplets. Our choice of the type and location of the clouds and the time and altitude of observation will permit virtual isolation of each of the particle growth mechanisms, diffusion, coalescence or accretion.

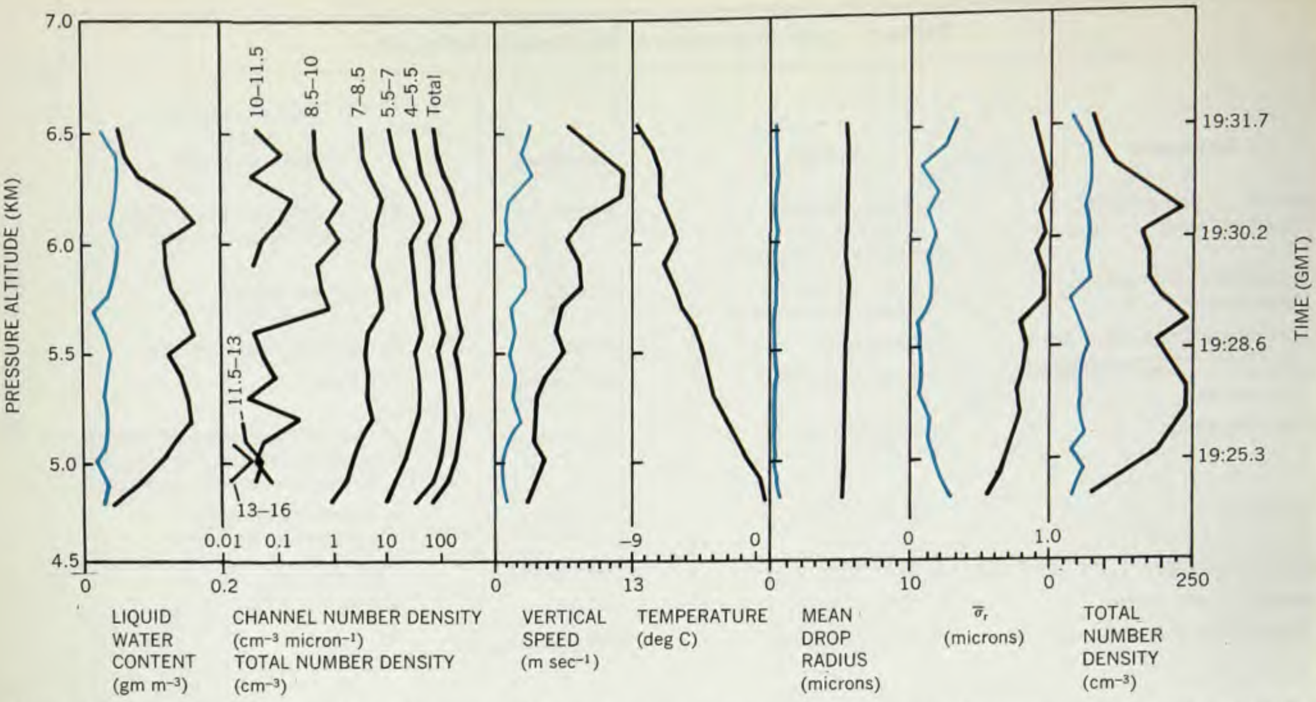
It is not possible to observe the collision or accretion efficiencies (or probabilities) directly in the atmosphere. Theoretical calculations of the collision probabilities are thought to be very good, but they must be checked in the laboratory. The fluctuations of the droplet distributions as a function of fluctuations in temperature and humidity of the rising air must be analyzed for their contribution to the growth of precipitation, and for this we need to know the collision, coalescence and accretion probabilities as accurately as possible. Inhomogeneities in the clouds are particularly important at this stage of our research as the present models are not designed to include them.

Much of the early information on convective motions in the atmosphere was obtained from observing soaring birds; however, observations of soaring birds have some obvious limitations for cloud research. At the National Center for Atmospheric Research we are imitating the flight characteristics of the birds with an instrumented sailplane. A sailplane does not pollute the air it is sensing as much as powered aircraft, or as birds do for that matter. Its slower air speed makes all cloud measurements easier and more accurate. The sailplane pilot can maneuver his craft into the updraft and circle to remain near its axis and rise with the air (except for the small sinking speed of the sailplane). The sailplane we use is instrumented to sense the air motion, temperature, altitude and cloud-particle information continuously. Data obtained this way are transmitted by telemetry to the ground to be recorded for immediate study and future analysis.

For this research we use the Explorer sailplane, a Sweitzer 2-32, purchased by the Explorers Research Corporation for mountain-wave research. It was recently donated to the National Oceanic and Atmospheric Administration and has been reinstrumented and operated by the Cloud Physics Program at NCAR for taking measurements in summer cumulus, mountain lee-wave clouds and the cloud-free atmosphere. This sailplane is shown in figure 1. The small wing above the canopy of the Explorer houses an optical background for a camera developed especially to photograph the distribution and orientation in space of cloud drops and ice particles. The faintly visible small boom protruding forward from the nose contains, at its tip, an automatic cloud-droplet probe to measure cloud-droplet size distributions each half second at temperatures as low as -30 deg C. Details of data accuracy and time resolution are shown in Table I.

The sailplane is piloted by Wim Toutenhoofd, who is a nuclear physicist converted to atmospheric physics and was once the soaring champion of Holland. The sailplane is somewhat like an early space capsule, crammed with a silver–zinc battery, compact solid-state low-power-consumption instruments and equipment and an fm telemetry link with a mobile ground station to avoid carrying the prohibitively excessive weight of magnetic tape recorders.

Measurements were made in numerous growing cumulus clouds during the



Averaged data obtained 12 August 1971 in the updraft of a cumulus congestus cloud in northeast Colorado. In each block colored lines show the standard deviations over 100-meter height intervals for the data depicted by black lines. $\overline{\sigma}_r$ is the standard deviation of ½-sec samples averaged over 100-meter altitude intervals. Curve labels show channel width in microns. Figure 4

summers of 1971 and 1972. After release from the tow plane at a suitable altitude, the sailplane is flown into the updraft under the base of the cumulus cloud. The pilot maximizes his upward velocity, centering on the core of the updraft, and moves upward through the base of the cloud to make quasi-Langrangian measurements of the cloud's microphysical and atmospheric state parameters. The sinking rate of the sailplane is usually small compared to the vertical velocity in the developing stage of the cumulus clouds.

Figure 4 is the computer plot of the data averaged over each 100-meter increment in altitude for the entire flight in the cloud of 12 August, 1971. The total liquid-water content obtained by summing all of the cloud droplets is shown in the first section of the computer printout. In each section of the diagram, with the exception of the second section ("channel number density"), the standard deviations from the black-line data for each 100-meter height interval are shown by the corresponding colored line. In the next-to-the-last section of the diagram the mean of the standard deviation of the radius of each individual sample averaged over 100 meters is shown as a black line. The corresponding colored line is the standard deviation from the mean of these averaged standard deviations. The variability of these recently obtained data is such that it is not possible to put the information directly into the present models. Work on this problem is proceeding, but it presents a formidable challenge to the adequacy of the models as they are now constructed.

A particularly striking feature of the data in figure 4 is the relatively constant mean drop radius; the spread of the distribution itself, which is of great significance in droplet-growth computations, changes considerably with small height and time intervals.

Photographs taken of the cloud droplets and ice particles situated in the free air between the wing-shaped object projecting upward from the sailplane and the top of the canopy give particle size, concentration and orientation in a volume, approximately the size of a 35-mm slide, placed horizontally roughly halfway between the projection and the canopy. The analysis of the photographs for particle size and concentration is much more tedious than the rest of the data, but gives a great deal of new information, and in the limited number of samples analyzed so far, relatively good correspondence with the droplet distribution.

Mountain-wave clouds

Standing waves appear in stable air over mountain chains like those in the Rockies of western Colorado. Steady-state clouds form around the crests of these waves. Figure 5 is a photograph of one of the type of lenticular clouds that provide us with a useful outdoor cloud-physics laboratory. Droplets are continuously forming and growing on the upwind side of each cloud and dissipating on the downwind side. The smaller cloud on the left in the photograph is several kilometers in vertical height and is trailing ice crystals from the upper (colder) portions. The entire cloud is very cold, being well below 0 deg C throughout, but only in the uppermost portions are enough ice crystals formed sufficiently large to cause a visible trail. Ice crystals formed in these small wave clouds sometimes trail a visible cloud for hundreds of miles downwind. Largely because of their steady-state nature, these clouds are better than anything that we can produce in the laboratory for integrated cloud microphysics experiments.

We can make regular measurements with the sailplane for several hours at altitudes exceeding 10 km on many days of the year in these clouds near Boulder, Colorado. Towed into the wave or other sources of "lift" (usually far beneath the base of the clouds), the sailplane quickly climbs to the upwind side of the cloud and enters, making continuous measurements as illustrated earlier for the cumulus clouds. The pilot, using the sailplane's sensitivity to air motions and the fast-response instruments on board, can maneuver to any desired feature of the wave motion and sample the atmospheric parameters and cloud microphysics with a great deal of flexibility, changing position and altitude to vary the conditions of the experiment. In this way the scientist-pilot can perform controlled experiments, including nucleation or other modification studies if desired.

From these flights (and those in the

Lenticular clouds northwest of Boulder, Colorado. This type of cloud is used by NCAR as their "outdoor cloud-physics laboratories." The photograph is by James D. Sartor. Figure 5

cumulus of last summer), *in situ* photographs of cloud droplets and occasional coexisting ice forms are available for study for the first time. See, for example, figure 6. The tiny white dots are supercooled cloud drops between 1.5 and 8.5 microns radius. The large white images are ice particles mostly outside the infocus zone of the camera. The particles must be in the infocus volume to determine shape and orientation. At a quite precisely determined distance from the camera lens, the images undergo a marked decrease in intensity independent of size—a feature that is used to compute the volume concentration of the particles.

The photographs are taken with a cloud-particle camera designed and developed by Theodore W. Cannon, another young nuclear physicist, who has become intrigued and motivated by the problems of the physics of clouds. Cannon is usually the scientist-observer in the rear seat of the sailplane, where along with obtaining photographs like those illustrated he continually works to improve the quality of the data from this instrument and its operation in the hostile environment (−20 deg C to −60 deg C) of these wave clouds.

Comparing the data

The data obtained in these field experiments usually contain the integrated result of several physical processes. Sometimes important processes happen too quickly or on scales too small to be observed directly in natural situations. This is particularly true of the collision and coalescence among cloud droplets or the accretion of small-cloud droplets by larger drops and ice particles. Studies on such microscopic scales must be made theoretically and in the laboratory.

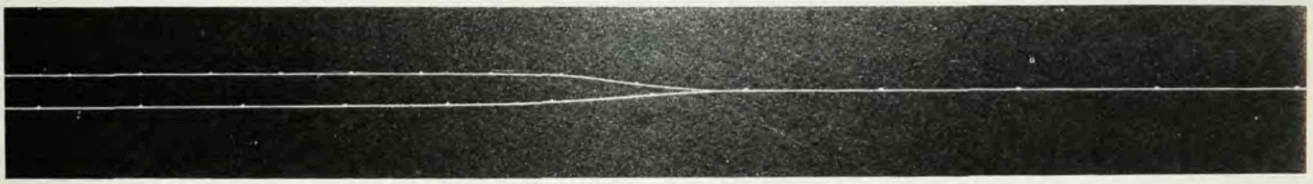
We are reasonably well satisfied with calculations of the collision efficiencies (probabilities) for cloud droplets, raindrops and spherical hail. The collision probabilities and the probability of coalescence of small cloud droplets upon collision have never been fully studied in the laboratory. The temperature and humidity and electrical properties of the particles themselves and their electrical environment can under certain conditions play a dominant role in the coalescence and accretion of particles.

We have investigated the use of electronically controlled streams of drops and synchronized photography to study coalescence and breakup of larger drops, but the limitations of this laboratory set-up, already fairly sophisticated, preclude doing studies in a general way that would be directly applicable to the physics of cloud drops.

In past studies of this type of collisions in our laboratories, spark discharges were discovered between freely falling charged drops by Allan Miller.[12] The electromagnetic radiation from these sparks of a few microns in length were studied by William Atkinson and Ilga Paluch[13] as a possible source of remote sensing information. William Atkinson and I[14] applied the results theoretically to a population of drops with charges and sizes appropriate to thunderstorms. Depending on the magnitudes of charge and size of the drops chosen, quasi-thermal emission of a few tenths of a degree Kelvin to over 100 K in extreme cases were predicted as possible from thunderstorms. A. A. Penzias and R. W. Wilson,[15] making observations with the highly sensitive microwave receivers at Bell Telephone Laboratories, have observed from thunderstorms 1–5 K noise that they attribute to this source. Recent studies at Cape Kennedy by Richard B. Harvey and Edward A. Lewis[16] have mapped radio-emission sources in clouds in the range 250 to 925 MHz; these observations suggest that remote-sensing techniques of this type could be of great utility for obtaining information on large drop sizes, charges and electric fields in convective clouds.

In the laboratory we now have a new instrument system, designed by Charles Abbot and Cannon,[17] for producing drops as small as 10 microns radius, which can be positioned for collision and coalescence studies under conditions more nearly simulating natural conditions. Collision efficiencies of highly charged drops are being studied now to compare with our theoretical calculations. Figure 7 is a streak photograph of the trajectories of colliding droplets of 19.1 and 15.8-micron radius charged to $+10.6 \times 10^{-5}$ esu and -62×10^{-5} esu respectively. The regularly sequenced high-intensity light flashes, which show as dots along the trajectories, are used to measure the drop ac-

Cloud droplets and ice particles in cumulus cloud, 15 June 1972, near Sterling, Colorado. The altitude was 7 km and the temperature -14 deg C. Ice-particle diameters are in the range 0.5–0.8 mm, and their concentration is approximately 200 per liter. Cloud droplet concentration is greater than 91 cm^{-3}; radii are not more than 100 microns. Figure 6



Collision between electrically charged droplets. The two droplets had radii of 19.1 microns and 15.8 microns. Their charges were $+10.6 \times 10^{-5}$ esu and -62×10^{-5} esu respectively; collision probability is 284. White "blips" are time markers. Figure 7

celerations and velocities. The theoretical calculations of fall velocity and collision efficiency are confirmed by the data obtained in this way when the drops are very small and the charge comparable to that expected in thunderstorms.

A particle control chamber has been designed by Cannon from a prototype developed by the INCA Corporation for the University of California at Los Angeles, and subsequently for the University of Missouri at Rolla. This chamber was designed to offset the fall velocity of one drop with a controlled vertical flow of air. The velocity of the flow is controlled from a few cm sec^{-1} (corresponding to the fall velocity of the smaller cloud droplets) to 10 meters sec^{-1} (corresponding to the fall velocity of the largest raindrops and small ice particles or hail.) The temperature can be controlled between $+30$ deg C and -30 deg C and the relative humidity from a dewpoint of -40 deg C to the saturation dewpoint or slightly more. An imposed vertically oriented uniform field can be placed in the test section with fields up to 2000 v cm^{-1}. In this chamber many of the drop-to-drop interactions and other growth processes involving ice particles and supercooled drops can be simulated realistically.

These controlled-flow chambers may be the cyclotrons of laboratory cloud physics. They allow for the first time studies of the microphysical interaction of droplets and ice particles to be made in a natural environment, unsupported by artificial supports or constraints.

Many important problems are yet unresolved in the variety of clouds and cloud processes that exist in the atmosphere. There is a real need to understand as much as possible about the physical processes in clouds for application and prediction needs, the removal of pollutants from our atmosphere and weather-modification efforts. The physical problems that have to be considered range throughout the entire gamut of the techniques used in fundamental physics and require the application of most of the information contained in classical physics. Many difficult extensions of presently available solutions are required.

The quest for accurate solutions to the problems of the physics of clouds presents a new challenge to the ingenuity of physical scientists for combining their training in physics and atmospheric science with imaginative physical experiments and new developments in mathematical and computational skills involving procedures that are partly deterministic and partly stochastic. This will require an unusual amalgamation of information and techniques that will lean heavily on the ability of the researcher to find the dominant processes in each of many different situations.

* * *

The National Center for Atmospheric Research is sponsored by the National Science Foundation.

References

1. J. D. Sartor, PHYSICS TODAY, August 1969, page 45.
2. V. J. Schaefer, Science **104**, 457 (1946).
3. B. Vonnegut, J. Appl. Phys. **18**, 593 (1947).
4. I. Langmuir, J. Meteorol. **5**, 175 (1948).
5. L. M. Hocking, Quart. J. Roy. Meteorol. Soc. **85**, 44 (1959).
6. U. Shafrir, M. Neiburger, *Collision Efficiencies of Two Spheres Falling in Viscous Medium for Reynolds Numbers up to 19.2,* University of California Press, Berkeley, (1964).
7. M. H. Davis, J. D. Sartor, Nature **215**, 1371 (1967).
8. M. H. Davis, J. Atmos. Sci., to be published (1972).
9. L. M. Hocking, P. Jonas, Quart. J. Roy. Meteorol. Soc. **96**, 722 (1970).
10. J. D. Sartor, J. Geophys. Res. **75**, 7547 (1970).
11. M. H. Davis, Quart. J. Mech. and Appl. Math. **17**, 499 (1964).
12. A. H. Miller, C. E. Shelden, W. R. Atkinson, Phys. of Fluids **8**, 1921 (1965).
13. W. R. Atkinson, I. Paluch, J. Geophys. Res. **71**, 3811 (1966).
14. J. D. Sartor, W. R. Atkinson, Science **157**, 1267 (1967).
15. A. A. Penzias, R. W. Wilson, Science **169**, 583 (1970).
16. R. B. Harvey, E. A. Lewis, ARCRL-72-0078 (1972).
17. C. E. Abbott, T. W. Cannon, Rev. Sci. Inst., to be published (1972). ☐