Cumulus-Type Flows in the Laboratory and on the Computer
Simulating Cloud Form, Evolution, and Large-Scale Structure

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The major problems associated with understanding cumulus clouds are connected with the microphysics of phase changes among the three phases of H$_2$O and the resulting small-scale dynamics, interactions between clouds and radiation, and the cloud-scale fluid dynamics that determines cloud forms, their entrainment characteristics, and their life cycles. Although these aspects are coupled, the present work is largely concerned with the last-mentioned problem. This has in general been controversial because field measurements are expensive to carry out and difficult to interpret. Many clouds have lifetimes of order 10$^2$–10$^3$s, and so are essentially transient flows (and no two of them are identical).

In the last two decades, many large-eddy simulations (LES) of cumulus convection have been reported, chiefly with the objective of obtaining statistical averages of such variables as entrainment and mixing over a collection of clouds. Among the potentially important uses of LES techniques is their partial use in “superparameterization” schemes. In contrast, the numerous attempts made to simulate cloud flows in the laboratory, based on such fluid-dynamical models as bubbles, thermals, and developing and steady-state similarity plumes, have generally been unsuccessful. Successful laboratory simulation of flows mimicking cumulus cloud forms, and presumably at least some major features of their cloud-scale dynamics, has recently been possible (Narasimha et al. 2011, N11 hereafter) using an apparatus specially designed for the purpose. This simulation is different from earlier work in three respects. First, it recognizes that the dynamics of a cumulus cloud must be affected by the latent heat release above the condensation level. Second, it explicitly takes into account the transient nature of the flow, comprising the stages of formation, development, and dissolution. Third, and most importantly, the total heat release employed in the laboratory simulation is chosen such that it is dynamically similar to that experienced by a natural cloud.

In this article we show selected examples of simulations of cumulus cloud flows using the same apparatus as in N11, as well as direct numerical solutions of the Navier-Stokes-Boussinesq equations, and summarize the dynamical insights that emerge from such simulations.

The Laboratory “Cloud-Flow Simulator.” The apparatus that we call a “cloud-flow simulator” (Fig. 1) utilizes water rendered electrically conducting (or “active,” by the addition of hydrochloric acid or salt) as a single-phase “cloud fluid.” The setup consists of a glass tank filled with deionized nonconducting water, which constitutes the ambient medium, with a plume of active fluid that issues into the tank from a false floor, underneath which is a “plume chamber” containing a heating coil that generates the buoyancy driving the plume flow. There is also an arrangement in the apparatus for “off-source” heat injection (i.e., heat addition away from the thermal source
in the plume chamber) to simulate latent heat release beginning at condensation level in a natural cloud. In the “Heat Injection Zone” (HIZ, Fig. 1), volumetric ohmic heating of the plume fluid is effected through a set of electrodes at different levels (housed in the electrode cage below the ‘HIZ’ label in Fig. 1) driven by a power source. The heating profile in the vertical and its history can be changed manually in real time, enabling simulation of a variety of flows of the cumulus cloud type. The flow generated in the apparatus may be appropriately called a “transient diabatic plume” (TDP) to emphasize the use of off-source heating in a cloud-type transient plume flow.

It is necessary here to briefly explain the sense in which the term “diabatic” is used. The latent heat released in a moist cloudy parcel of natural nonprecipitating clouds is adiabatic if the total energy of the parcel is conserved, or “pseudoadiabatic” if condensation products are removed. However, here we adopt a Boussinesq-type approach that focuses on the dynamics of the cloud fluid, treating density differences as inertially insignificant in the cloud flow, with heat release due to condensation significantly enhancing buoyancy. Latent heat can then be considered as “external” to the principal carrier of the cloud fluid—namely, dry air. In this sense, an important link between cloud fluid dynamics with thermodynamics and microphysics is through off-source heat addition (Fig. 6, N11). The effect of in-cloud heat release can then be investigated through prescribed but dynamically scaled off-source diabatic heat injected into a laboratory plume.

The off-source volumetric heating may be characterized by a nondimensional parameter called the bulk heat-release number \( G \), which is a measure of the ratio of the rate of the off-source heating \( Q \) to a characteristic flow kinetic energy flux \( \rho U^3_b \), where \( \rho \) is density and \( U_b \) is plume center-line velocity at \( z_b \), representing the height of the cloud base in a natural cloud or the beginning of the HIZ in the cloud simulator. More precisely:

\[
G = \frac{g\beta Q}{\rho c_p b_b U_b^3},
\]

where \( \beta \) is coefficient of thermal expansion of the cloud fluid, \( g \) is acceleration due to gravity, \( c_p \) is specific heat at constant pressure, and \( b_b \) is the velocity width at cloud base. Typical values of \( G \) in natural clouds lie between 0.1 and 2, and in the laboratory experiments to-date between

<table>
<thead>
<tr>
<th>Laboratory clouds</th>
<th>Natural clouds</th>
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<tbody>
<tr>
<td>Plume (or jet)</td>
<td>Main vertical convective motion</td>
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<tr>
<td>Current carrying acid in plume fluid</td>
<td>Saturated water vapor in cloud</td>
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<td>Off-source ohmic heating</td>
<td>Latent heat release by condensation/freezing</td>
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<tr>
<td>Concentration stratification at ( z_{ls} )</td>
<td>Low-altitude inversion layer (e.g., at the top of the atmospheric boundary layer)</td>
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<tr>
<td>Temperature stratification at ( z_{us} )</td>
<td>High-altitude inversion layer (at the tropopause or due to trade winds)</td>
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<tr>
<td>Constant ambient temperature (away from stratification layers)</td>
<td>Neutrally stable atmosphere (constant potential temperature)</td>
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Fig. 2. Simulated cumulus-cloud evolution (a) and forms (b–d). For each, the history of the heating profile in the vertical across electrodes 1 to 6 is shown in the left rectangular graph, the power level being indicated by a color code. The history of the total heating injected into the flow and the velocity of the fluid at the orifice are shown in the right rectangular graph. Some of the important parameters characterizing the flow are included in a panel accompanying the figure. Here $Re$ is the Reynolds number, based on orifice-exit velocity and orifice diameter; $T_a$ is ambient temperature. For other symbols, see caption of Fig. 1. Note that the experiment for the evolution in (a) was conducted (without replacing the ambient water) immediately after the one presented in N11 that culminated in a cumulus fractus with “cloudy” parcels in irregular descent from its base. The debris of this cloud flow can be seen in the background of the images in (a) (a situation not uncommon in the atmosphere).
0.04 and 0.4, ensuring a significant overlap between the two (see online supplement for further details).

While overall dynamical similarity is achieved in the apparatus, the heating profile in the vertical raises an issue. A commonly held view in the meteorological literature, based on the adiabatic parcel model, puts the rate at which latent heat is liberated in a saturated parcel as proportional to the vertical velocity, as that determines the rate of adiabatic expansion and cooling experienced by the parcel. The actual heat released by phase change in the atmosphere depends upon many factors, such as the amount of water vapor present, the presence and distribution of condensation nuclei, degree of supercooking, etc., assuming of course that the Clausius-Clapeyron equation is satisfied. Such a complex association between heating rate and parcel dynamics is not directly simulated in the laboratory, but the present apparatus can simulate certain interesting aspects of cumulus-type flow, as listed in Table 1. This is supported by the laboratory results obtained so far, which suggest that some fundamental features of the response of a turbulent cloud-fluid plume to significant diabatic heating shed light on the dynamics underlying cloud-like flows (see N11).

Before proceeding further we note that we are dealing with nonprecipitating cumulus clouds. Furthermore, the effects of evaporative cooling present in atmospheric clouds (although capable of simulation in the apparatus) are not included. Instead, we focus our attention in the first instance on the effect of heat release on entrainment dynamics. This in turn offers explanations of many large-scale features of cumulus clouds (N11), suggesting that buoyancy enhancement due to phase change could be the distinguishing feature of a cloud flow compared to a dry plume. As illustrations, we first present selected whole-field flow visualization pictures obtained in the apparatus.

**LABORATORY CLOUD-FLOW FORMS AND EVOLUTION.** We begin with one example of a simulated cloud life cycle (Fig. 2a) through a sequence of five snapshots, at time instants $t_1$ to $t_5$ respectively.

In the initial stages of development the active plume first takes the form of a shallow dome-shaped cumulus congestus (Fig. 2a at $t_1$; cloud types are designated as in the International Cloud Atlas of 1975), and at $t_2$ that of a “mushroom-shaped” congestus. Soon thereafter, the heating switches to a “top-loaded” profile, accelerating the fluid in the upper half of the HIZ so rapidly that it is about to detach from the rest of the cloud flow at $t_3$. Even as the plume flow is still turned on (or equivalently for a natural cloud, the plume-generating “hot patch” on the surface is still active). The large local buoyancy addition due to the top-loaded profile mimics the effect of the steep lapse rate noted in Namias’s 1939 atmospheric study in *Monthly Weather Review*. Such a breakaway is different from the one shown in N11 (their Fig. 3f), wherein the cloud as a whole detaches from the lower-level stratification (LLS) interface after the plume is turned off at the source, whose atmospheric analog is cessation of convection due to surface cooling. Successful simulation of two different types of cloud detachment observed in nature suggests that some of the underlying dynamical processes can be explored under controlled conditions in the present simulator.

After the cloud-top separation, flow development in the HIZ starts afresh. At $t_4$, the heating profile is similar to that at $t_2$, and the forms of the cloud flow are also similar, showing flow-type repeatability in the simulator. This enables generation of statistics on transient flows by running an ensemble of identical experiments. For $t_4 < t < t_5$, the heating profile is unchanged, the “mother” cloud slowly starts growing again into a cauliflower-shaped cumulus congestus (Fig. 2b) and looks rather like a cumulus “tower” at $t_5$ (Fig. 2a). Meanwhile, active fluid accumulates at the LLS and spreads across it. With the bottom-loaded heating profile this results in a cloud base wider than the cloud top, exhibiting a curious “head-on-a-shoulder” shape seen in Fig. 2b.

**Fig. 3.** A schematic of the variation of the entrainment coefficient $a_E$ with height in a steady diabatic jet or plume. The abscissa is the value of $a_E$ normalized by its value $a_{Eb}$ at the beginning of heat injection, which corresponds to cloud base; $L$ is the height of the HIZ, with its base at $z_a$. For details about the heating scenarios, see Diwan et al. (2011). (Based on N11).
Figure 2c shows a case where—except for a short initial period—moderate heat is added over almost the entire HIZ until the instant of the snapshot. This causes overall rising motion of the active fluid driven mainly by buoyancy forces, resulting in a flow with almost constant width.

The cloud in Fig. 2d exhibits a jagged, irregular boundary with diffuse, fibrous edges indicating the evaporating stage of a cumulus “fractus”—the second species simulated here. At the time of the picture, the simulated flow is nearing the end of its ascent and starts sinking and dissipating shortly thereafter, whereas the natural cloud has already entered the dissolving stage.

The above discussion illustrates how a variety of cumulus cloud forms and life cycles can be understood in terms of flow, heating, and stratification parameters as examples of TDP flows. Combined with accurate velocity and temperature measurements, it now appears feasible to investigate certain aspects of cloud-type flow evolution in a replicable laboratory environment. Such a project is currently underway at the authors’ laboratory.

**THE ENTRAINMENT.** The simulator enables measurements of mass flow in steady or transient diabatic jets and plumes using laser Doppler and particle image velocimetry (LDV, PIV). Most of the experiments carried out to-date have primarily focused on steady diabatic flows, which may be seen as simulating the lower (hence more mature) parts of a steady deep-convection cloud in the atmosphere, and have the advantage of providing accurate measurements of long-time averages. Some preliminary transient flow data have been reported by Vybhav et al. (2012).

A detailed analysis of the data so obtained (reviewed by Diwan et al. 2011) reveals the presence of four regimes in a steady diabatic round plume, as shown schematically in Fig. 3 (see Narasimha 2012, hereafter to be called N12). The data are presented in terms of the entrainment coefficient $\alpha_z$, defined as $(2\pi \rho b U_c)^{-1} \frac{dm}{dz}$ where $m$ is total vertical mass-flow rate at height $z$ [calculated as $m=\int_0^\infty 2\pi r \rho b r dr$, the upper limit marking the edge of the mean velocity profile in the core flow], $\rho$ the fluid density, $U(r)$ the mean vertical velocity, with $U_c=U(0)$. $r$...
the radial coordinate, and $b$ the velocity width [defined typically as $U(r=b)=U/e$]. In general, the entrainment coefficient relative to the value just before heat release (i.e., at cloud base) continues to remain approximately the same for a short distance into the HIZ (Regime I, see Fig. 3). Thereafter it starts to increase, reaches a maximum in the middle or upper levels of the HIZ, and then starts decreasing (Regime II). In Regime III, it falls below the value obtained in self-similar steady plume flow. Eventually, the entrainment coefficient drops toward zero—and may even go slightly negative (Regime IV).

**NUMERICAL SIMULATIONS.** Direct numerical simulations (DNS) of the TDP can provide detailed information on variables that are difficult to measure, such as vorticity, the baroclinic torque, dissipation, and eddy fluxes of momentum, heat, and vorticity. We present here some preliminary results from a DNS of the TDP based on the Navier-Stokes-Boussinesq equations (NSB). Details about the simulation will be found in the online supplement.

Figure 4 presents a selection of results obtained from such numerical simulations. Figures 4a,b compares two matched pairs of natural and computed clouds. (The latter are obtained from computed passive-scalar concentrations in the NSB solutions, using a suitable concentration threshold to define cloud edge, and processed to produce a 3D volumetric view.) One pair (Fig. 4a) represents a cumulus congestus that shoots up as a tower and has a distinct plume head (simulated in the laboratory, see Fig. 3b, N11), and the other (Fig. 4b) a small cumulus with cauliflower-type head or dome. The computations mimic the general form of the natural clouds. The entrainment coefficient shown in Fig. 4c may be compared with the experimental results in Fig. 3 for a steady diabatic plume. It will be immediately seen that over the lower part of the TDP the general variation of $\alpha_{E}$ is roughly similar to that in Fig. 3, but there is a strong difference in the region of the plume head, showing a steep drop in $\alpha_{E}$ to negligibly large values. This suggests that the qualitative behavior of the TDP in the region within and just above the HIZ (which has experienced heating for a longer period) is similar to that in the steady diabatic plume, but that the plume head has distinct dynamics of its own.

Figure 4c(ii) (inset) presents isosurfaces of the instantaneous azimuthal vorticity. It is seen that there is a dramatic rise in the vorticity (especially at the small scales) following heat release: compare the sparse isosurfaces below the region of heat addition. This is consistent with the results on enstrophy spectra obtained in an early temporal simulation of a diabatic jet in a periodic box (Basu and Narasimha 1999). The small-scale vorticity, which defines the edge of the turbulent region in the TDP (as in any other shear flow), is characteristic of the crinkly edges seen in many cumulus clouds.

It is now interesting to return to Fig. 3. The variation of the entrainment coefficient sketched there cannot yet be understood in precise detail, but the following explanation is plausible and consistent with data available to date (N12). In Regime I, the turbulence structure has not yet been sufficiently affected by the additional heat it has started receiving, so it remains more or less unaltered. Experimental evidence consistently indicates that the flow width enlarges slightly in this regime. As heating begins to slow down the velocity decay that would normally occur in the conventional plume, or even to accelerate the flow (through the action of an enhanced baroclinic torque; see online supplement), the entrainment coefficient increases. In Regime II, it reaches a maximum, and thereafter begins to decrease, because the heating (through the mean and fluctuating baroclinic torques) has by then begun to disrupt the coherent structures in the plume flow, as seen strikingly in Fig. 4c(ii). Incidentally, the sinking velocities generated just outside the edges of the TDP through the operation of the mean baroclinic torque (Fig. ES2, online supplement) now fold down the “tongues” of core fluid protruding into the ambient in the absence of heating, suppressing the normal larger-scale process that leads to entrainment. As this action continues, the entrainment falls below the similarity theory value in Regime III. The progressive disruption of coherent structures has been demonstrated in earlier experimental work (Bhat and Narasimha 1996, Venkatakrishnan et al. 1999).

Finally, beyond the zone of heat release the entrainment coefficient drops to negligible values, as the buoyancy force due to diabatic heating dominates the flow, which continues to rise in a “hot” cumulus tower. Eventually, of course, the effect of the heat added in the HIZ starts to weaken as the cloud flow is diluted (by the cooler ambient fluid) and the flow relaxes slowly back toward a normal plume (not shown in Fig. 3) in the steady case, although this may be interrupted in the atmosphere by a second phase change in the form of glaciation. Glaciation can in turn set off a second cycle of heat release, development, and dissipation.

The steady diabatic results of Fig. 3 compare favorably with the recent LES computations by Romps and Kuang.
(discussed in a 2010 Journal of the Atmospheric Sciences article) of an entrainment-related parameter called “purity” (Fig. 5, N11). In the transient case illustrated in Fig. 4, the tower culminates in a relatively wide plume head across which there is considerable detrainment.

In summary, based on an analysis of the experimental data and some supporting numerical experiments carried out so far, the apparently strange behavior of cloud flows in contrast to classical plumes may be explained in general terms through the baroclinic torque that results from heat release. It only needs to be added that lower entrainment implies lower dilution from ambient fluid, and could be responsible for greater mixing in the inner flow, of the kind that has sometimes been reported in natural clouds in the form of a “protected core” and is seen in the experiments as well. This mixedness is consistent with the explosive growth in small-scale turbulent vorticity (and consequently in interface area), driven by a strong fluctuating baroclinic torque.

CONCLUDING REMARKS. This article has described how recent experimental work has identified the transient diabatic plume as a basic flow model that enables laboratory simulation of cumulus cloud forms and their complete life cycles. Our approach decouples the fluid dynamics of the cumulus cloud from the thermodynamics of phase change by treating the adiabatic or pseudoadiabatic latent heat release in the cloud as a diabatic heat injection in a transient plume. As a result, a plausible physical and mechanistic picture of various cumulus-flow characteristics is beginning to emerge from both laboratory and numerical simulations. In such explanations, the baroclinic torque plays a major role by indicating the nature of the differences from the classical plume, thereby providing a new perspective on the cumulus cloud problem. By highlighting the roles of the history of the heating profile and the baroclinic torque, the work offers several new parameters that may be relevant to cloud modeling—for example, the entrainment may be related to gradients of buoyancy. A correlation involving temperature gradients in the flow and the entrainment velocity could provide important clues for fluid-dynamical modeling of cloud-scale flows in the atmosphere. Other similar proposals for new models can be evaluated on the basis of the data that are beginning to be available.

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FOR FURTHER READING


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