Simulating cloud flows in the lab to understand their dynamics

Roddam Narasimha
Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore

*E-mail of presenting author: roddam@caos.iisc.ernet.in

Abstract Cumulus clouds are one of the biggest uncertainties in climate change science, and cloud models are a weak link in understanding tropical circulations. One major issue over the decades has been the apparently anomalous behavior of entrainment in clouds as compared to classical equilibrium jet and plume flows. Here we show results from recent cumulus flow simulations in the laboratory, in an apparatus that permits active control of the flow through diabatic heating. The heating is dynamically scaled to simulate latent heat release on condensation of water vapour in the cloud. In these simulations the cumulus cloud is viewed as a transient turbulent plume. It is shown that by appropriate management of flow variables, a variety of cumulus flow-types can be generated in the lab. Furthermore, the evolution of a cumulus cloud flow, all the way from its initial phase as a classical 'cauliflower' type cumulus congestus to its final decay as a cumulus fractus, can be reproduced. A careful reanalysis of laser velocimetry data in the lab shows that heat injection to a jet or plume alters entrainment characteristics drastically. Flow visualization indicates that this effect is attributable to structural changes in the flow due to heating.

Keywords Cumulus clouds; Tropical circulations; Simulations; Entrainment; Flow visualization

1. Introduction

Clouds have for long excited the imagination of man, and have been the subject of much inspired poetry – in India most famously the *Megha-dūta* (The Messenger Cloud) of Kālidāsa (~ 6th c. CE?). For the last two centuries they have become the object of modern scientific inquiry, since the British chemist Luke Howard began to classify them into genera, species etc. as in botany. Among the many cloud types he identified were the familiar cumulus, cirrus and stratus. Of these the type known as cumulus has been the object of much attention, as it plays a crucial role in meteorological dynamics.

Cloud parameterizations have a strong effect on the operational success of general circulation models in predicting the state of the monsoons, which affect the economic life of all South Asian countries, but to this day our understanding of cloud dynamics is still incomplete. Clouds also are a weak link in climate change science – they have been called the 'big bad player of global warming' by Kerr [1].

Cumulus clouds constitute one of the most challenging problems in tropical meteorology. During the last fifty years various attempts have been made to analyse the cumulus cloud as a problem in fluid dynamics. Turner [2] made experimental observations of a thermal (an instantaneous point source of buoyancy flux) as a model for the cloud, and later proposed a starting plume as perhaps more appropriate. Morton, Taylor & Turner [3] proposed an entrainment model for plumes based on similarity theory. Field observations (e.g. Paluch [4]) however showed that the similarity plume theory could not explain the behaviour of atmospheric clouds.

For the last fifteen years or so a group of us at Bangalore (including Prof G S Bhat at CAOS / IISc, more recently Prof K R Sreenivas and Dr S Diwan at JNCASR) have been studying the fluid dynamics of cumulus clouds. The approach is to view the cumulus cloud as a special class of turbulent shear flows, both experimentally and computationally. Here I consider only the experimental work, which is centred around a simulation facility that is basically a water tank in which jets and plumes issue vertically upwards from the floor (Figure 1). At the heart of the simulation is the idea that what makes the cloud a very special turbulent shear flow is the release of latent heat of condensation of water vapour into liquid water, as warm moist air rises in the atmosphere and cools to the appropriate temperature. The major parameter that governs the dynamical similarity of flows subjected to such 'off-source' heating is the heat release number [5]

$$G = \left(\beta g / \rho C_p\right)\left(Q / b_b U_b^3\right)$$

where β is the thermal coefficient of expansion of the cloud fluid, g is acceleration due to gravity, ρ and C_p are respectively density and specific heat at constant pressure of the ambient fluid, Q is off-source heating rate (W / m^3), and b_b and U_b are the length and velocity scales at the condensation level in the cloud or the beginning of the heat injection zone (HIZ) in the apparatus.

Heat release in the atmosphere is of order 1 W / m^3, and G is in the range 0.1 to 2.0 [6]. To attain similar values in water needs heat release of order 4 MW/m^3, which is a very convenient 1-2 kW for a flow volume of 250 cm^3.

The new facility built recently at JNC, shown in Figure 1, enables us to control both the temporal variation of Q (its history), and its spatial distribution in the vertical (its 'profile'). Furthermore, we can manage these flows in an active control mode, i.e. we can change both heating history and profile to 'steer' them towards a target cloud flow, based on current observations of the state of the flow. It is also possible to capture the cloud as a finite-life evolving flow, from its initial stages when it is a cumulus congestus type (the classical 'cauliflower') to the final decaying stage (cumulus fractus). The life time of a natural cloud varies from 10 to 30 min. or so; hence it is often not in a proper steady state.

A typical example of the results that can be obtained from such experiments is shown in Figure 2, which compares a natural cloud with the simulation. Below the paired pictures are two panels which show the heating history (left) and provide information on the heating profile (right). For about 20 s after heat injection commences the heating profile is bottom-loaded, and gets the cloud flow started vigorously when it is still relatively young. The profile then gets more nearly uniform. Some 15s before the pictures were taken the heating profile changes to top-loaded, and the flow now gets accelerated near the top. This loading history produces a cloud that has a narrow, tower-like structure topped by a cumulus head. The cloud so generated is a cumulus congestus type.

Following the classification accepted by the World Meteorological Organization [7], we are able to reproduce two genera (cumulus, alto- / strato-cumulus) and three species within the genus cumulus (congestus, mediocris and fractus).

From the results of these experiments we propose that an appropriate physical flow model for the cumulus cloud is a diabatically heated transient plume [8]. The heating is essential, otherwise the unusual entrainment characteristics of the cloud cannot be explained. The source of the cloud – its origin typically as rising air from a hot spot on the surface – lasts much longer than for a thermal. During its infancy it behaves like a starting plume, but at later stages it can become an isolated cloud, and still later (perhaps cut off from its source near the surface) it gets fragmented and dissipates itself (as a fractus). Recent experiments can track the whole life-trajectory of a cumulus cloud.

A recent reanalysis of laser velocimetry data [9] shows that the entrainment coefficient of such a cloud is not a constant, as assumed in similarity theories. During its development immediately following condensation and latent heat release it typically shows a slight increase, then reaches a maximum, and finally falls relatively rapidly to very low values, possibly even to zero.

Experiments of the kind described here promise many fresh insights into the fluid dynamics of cumulus clouds.

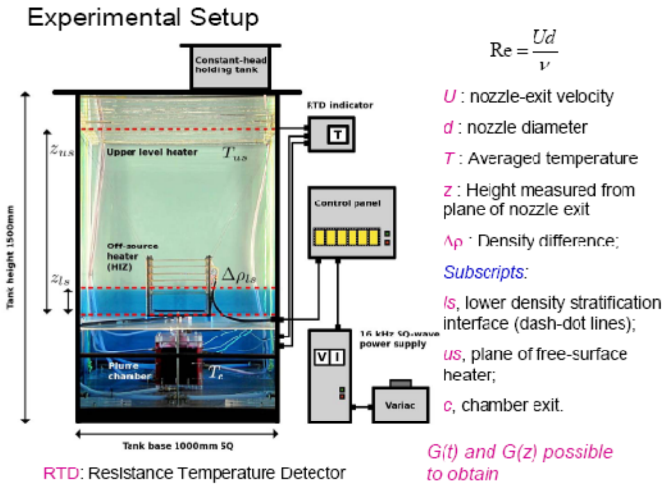

Figure 1: The apparatus for simulation of cumulus cloud flows.

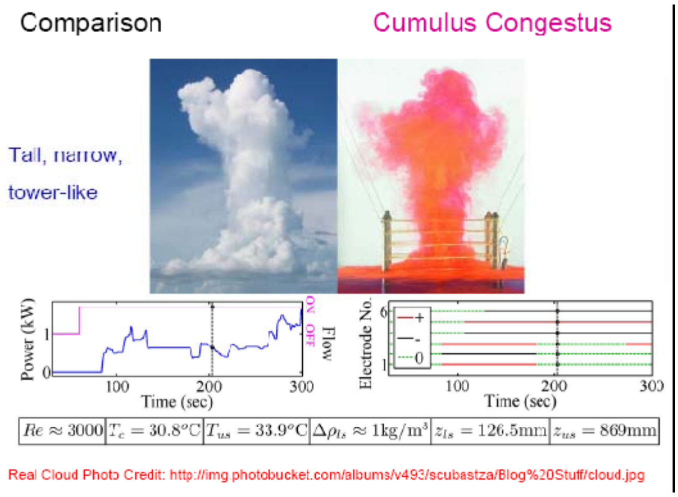

Figure 2: A typical experimental simulation of a cloud flow, compared with a natural cloud

2. Acknowledgements

The recent work reported here has been carried out in collaboration with Dr S Diwan, Mr D Subrahmanyam, Prof

K R Sreenivas and Prof G S Bhat. We are grateful to JNCASR for support.

References

[1] R A Kerr 2009 *Science* 325:76

[2] J S Turner 1973 *Buoyancy Effects in Fluids*, CUP

[3] B R Morton, G I Taylor, J S Turner 1956 *Proc. R. Soc.* London A234:1-23

[4] I R Paluch 1979 *J. Atmo . Sci.* 36:2467-78

[5] G S Bhat, R Narasimha 1996 *J. Fluid Mech.* **325**:303-330

[6] L Venkatakrishnan, G S Bhat, A Prabhu and R Narasimha 1999 *J. Geophysical Res.* 104:14,271-14,281.

[7] WMO *International Cloud Atlas*, WMO

[8] Narasimha R, Diwan S, Subrahmanyam D, Sreenivas K R, Bhat G S. In preparation.

[9] S Diwan et al. In preparation.