Cloud MicroAtlas*

Rama Govindarajan and S Ravichandran (Croor Singh)

We begin by outlining the life cycle of a tall cloud, and then briefly discuss cloud systems. We choose one aspect of this life cycle, namely, the rapid growth of water droplets in ice-free clouds, to then discuss in greater detail. Taking a single vortex to be a building block of turbulence, we demonstrate one mechanism by which we believe droplets grow rapidly.

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Introduction

Look up at the sky! You are likely to see clouds pretending to be large gentle puffs of cotton, standing still or moving lazily[1]. Fly through, and you feel the turbulent, and even violent, dynamics within. A revealing experiment is to take a video of a cloud, say for an hour, and play it fast.

[1] Some of this text appeared in a recent newsletter of the ICTS.

High clouds probably form by a miraculous circumstance called 'volumetric heating' [1]. Imagine a plume of smoke coming out of a chimney. The plume is hotter than its surroundings, and therefore lighter and buoyant, so it rises through the air. Close to the mouth of the chimney, its colour is dark grey, due to the soot it carries. Moving up, its colour becomes lighter and lighter, and then practically vanishes. This is because surrounding air is 'entrained' into the plume, i.e., the plume fluid drags along some surrounding air and mixes with it, effectively sharing its soot concentration, its heat, as well as its momentum with it. So along with the colour, the temperature and the upward velocity of the plume also reduces with height, until the plume is extinguished at a height which scales with the initial buoyancy flux and the lapse rate of the atmosphere [2]. A cloud begins life as a parcel or plume of air which, instead of soot, carries water vapour that has evaporated from the oceans or the land surface. The arguments

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*Any resemblance to the title of David Mitchell's book is purely intentional!

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for a plume suggest that a cloud should lose its water vapour as well as its upward momentum, if any, to the surrounding air and become incapable of causing rain. For typical conditions, this height is no more than a few hundred metres. On the contrary, a monsoon cloud stands several kilometers tall and can conserve enough water to cause rain [2]. How?

[2]A cloud that is tall, and appears tower-like, is called a 'cumulus' or a 'cumulus cloud' (plural: cumuli). Large cumulus clouds that can produce rain are called 'cumulonimbus' clouds, from the word 'nimbus' meaning rain.

Every parcel of air which contains some water vapour will not become a rain cloud, so let us call such a parcel a 'rain cloud aspirant' or RCA. Rain cloud aspirants must of course have sufficient initial buoyancy or upward momentum to begin their rise. Now the temperature in the atmosphere falls by about 7 degrees Kelvin per kilometer of height [3]. Correspondingly, the saturation vapour pressure falls, i.e., the partial pressure of a given parcel of air, if it contains sufficient water vapour, will equal the saturation vapour pressure at some height. This height is known as the 'lifting condensation level'. As the RCA rises past this height, volumetric heating can spring into action. At every height, some water vapour within the parcel condenses to liquid water. The latent heat of condensation gives additional buoyancy to the parcel, enabling it to rise further and allowing the process to continue. To see a variety of cloud shapes that can form out of this process, see [4]. For reasons not understood yet, entrainment seems to be far lower in a volumetrically heated plume than in a normal one where no phase change occurs. Entrainment, even in a simple turbulent shear flow is not understood quantitatively. When fluid flow and thermodynamics co-evolve, things are much more complicated. Due to this lowered entrainment, the water vapour is not all frittered away into the ambient.

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The next step is the formation of rain drops. This is discussed in some detail in the next section. An RCA that can create enough large raindrops which fall upon the earth has succeeded as a rain cloud. We have discussed a single cloud so far, and there are myriads of unanswered questions here. The next level is to understand why clouds aggregate and form planetary scale structures, and when and why cloud bands migrate, especially in the meridional direction. Such migration, over some range of longitudes spanning India and its neighbourhood, of the equatorial cloud band known as the 'Inter-Tropical Convergence Zone' (ICTZ), is generally accepted to bring India its summer monsoon [5].

The Indian monsoon is a dramatic event which takes place every year between June and September. Its onset is sudden and beautiful, and it has been a preoccupation of scientists, poets, musicians, economists, farmers, and the rest of us water-drinkers for at least twenty-five centuries to our knowledge. The pattern is similar every year, although variations of about ten percent do occur from year to year. These minor variations result in prosperity or great distress, depending on their sign [6].

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Clouds are but a small part of what determines the Earth's climate. But they are also among the most difficult. A majority of the Earth's surface, at any given time, is covered by clouds. Clouds are acknowledged to form the biggest uncertainty in climate predictions. Whether clouds will aggravate global warming or make it milder is not known yet, though it is believed that increased sea surface temperatures will increase convective activity and probably cloud formation. The reigning dogma is that low clouds reflect more and therefore cool the Earth's surface, whereas high clouds act like blankets to keep the heat in. Monsoon clouds are thin and tall, and do both [7].

Global climate models are unable to predict the Indian Monsoon as of now, for reasons to do with our inadequate knowledge of clouds, our inadequate understanding of many unique processes in the Bay of Bengal, our inability to resolve spatial scales due to computer limitations, and many other things. These will challenge us for the next decade at the very least.

Droplet Growth

In this section, we address the 'droplet growth bottleneck', an open question in cloud physics concerning the growth of water droplets in clouds. The life-cycle of a cloud is summarised in *Figure* 1. Since we are interested in water droplets, we are concerned with the 'microphysics' block in the figure. In particular, we are

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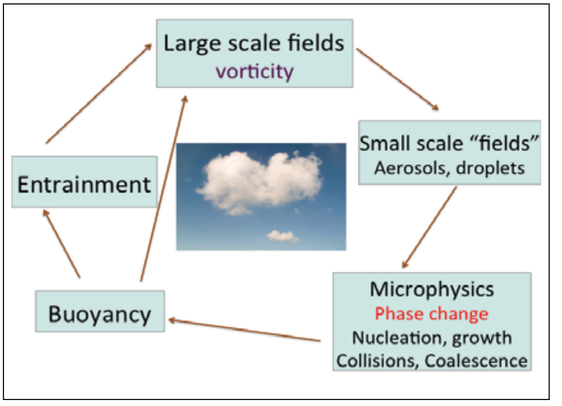

Figure 1. The cloud life-cycle, adapted from Narasimha *et al*. [4]. The large scale vortical structures dictate the motion of small scale objects like aerosol particles. These then cause phase change, which release heat into the flow. The increase in heat reduces density locally, giving buoyancy to the cloud. The resulting potential energy is then converted partially to kinetic energy, which manifests itself as turbulence, i.e., large-scale structures.

interested in how large-scale fields affect the microphysics. We do not have a complete answer, but only a possible mechanism. The most comprehensive reference we know of on the subject of cloud microphysics is the book by Pruppacher and Klett [8].

Consider an RCA that has reached its lifting condensation level. Above this height, the water vapour in the RCA is supersaturated. In spite of this, for significant condensation to take place, the RCA needs a significant density of aerosol particles within it, which can act as cloud condensation nuclei. Aerosol is crucial to this process [9], because in the absence of solid or liquid surfaces on which the water vapour can condense on, one needs a supersaturation of several hundred percent for spontaneous condensation[3] to take place, whereas supersaturations rarely exceed a couple of percent in a cloud. For the droplet to grow bigger, its radius must be larger than what is called a Kohler radius, for reasons we will not go into now, but can be worked out easily[4]. Since there is usually sufficient aerosol concentration everywhere to trigger condensation, the RCA is now technically a cloud[5], and if large enough, can be seen by us below. It is still not a rain cloud, unless the droplets grow to a large enough size to fall under gravity, and not re-evaporate too much along the way.

Aerosol particles are of the order of microns in size, so this is the initial size of a typical water droplet. A droplet of this size grows if it continues to live in a supersaturated environment, by a simple diffusion of water vapour towards its surface, followed

[3]This kind of condensation is said to occur by 'homogeneous nucleation'. See Section 5.10, pp.238, in the book by Bohren and Albrecht [10].

[4]See, Chapter 5, pp.254, in the book by Bohren and Albrecht [10].

by condensation. This growth is fairly quick, i.e., a droplet takes less than half a minute (if the supersaturation is 2%, say) to grow to a size of 10 microns. Beyond 10 microns, droplet growth by diffusion is slow, and would take several days to create a rain drop. However, the lifetime of a cloud is less than a day, and rain can happen within an hour. On the other hand, droplets bigger than 50 microns can grow very fast by the mechanism described in the final paragraph of this section. What makes the droplets grow in a matter of ten minutes from 10 to 50 microns is not sorted out yet, and is termed the 'droplet growth bottleneck'. Here coalescence of droplets to make bigger drops is very important, rather than the growth of individual droplets by condensation. But the droplet number density is low in clouds, and thus at the face of it, the frequency of two droplets colliding and coalescing is small.

[5] The World Meteorological Organisation defines a 'cloud' as – "a hydrometeor (fancy word for mass of air containing water in some form) consisting of minute particles of liquid water or ice, or of both, suspended in the free air and usually not touching the ground [which] may also include larger particles of liquid water or ice as well as non-aqueous liquid or solid particles such as those present in fumes, smoke or dust."

In general, the collision rate of a drop of radius a_0 in a gas of droplets of size a_1 is [11],

$$R = \pi\epsilon N\,(a_0 + a_1)^2\, v_{rel}, \tag{1}$$

where N is the local number density of droplets, v_{rel} is the relative velocity between droplets of the two sizes, and ϵ is the collision efficiency. To increase the frequency of collisions, we need a mechanism to make droplets cluster into smaller regions of space, i.e., to make N higher.

Flow in an RCA is usually turbulent[6]. Turbulence has a counter-intuitive effect on inertial droplets and solid particles, i.e., objects of finite size whose density is different from that of the surroundings. When we put milk into tea and stir it, turbulence mixes the milk in, until the concentration of milk is uniform everywhere in our tea. On the other hand, if we start with a uniform concentration of inertial particles, turbulence actually demixes this suspension and creates stringy regions of high particle-concentration, with practically no particles elsewhere. It is believed that turbulence has an important role to play in bridging the droplet growth bottleneck, by creating regions of extremely high droplet number density where frequent collisions and coalescence can take place,

[6] Any flow where the product of typical length and velocity scales is far far bigger than the kinematic viscosity is highly likely to be turbulent. For typical clouds, the product of length and velocity is about 10^7 times as much as the viscosity.

but this has not been quantitatively established.

The most important trait of turbulence in this context is its vorticity, which is the curl of the velocity vector. In a typical turbulent flow iso-vorticity contours appear like long floppy spinning tubes[7]. Each vortex induces a velocity everywhere in the flow, i.e., it makes all other vortical and non-vortical regions move around[8]. Heavy inertial particles, such as water droplets in a cloud fluid, get centrifuged out of vortical regions. Such droplets therefore preferentially sample regions of the flow with low vorticity, and it follows that droplets are more dense outside vortical regions. The literature on this topic is discussed in [13]. We recently showed [14] that droplets which originate within a special region close to a vortex, which we call a 'caustics region', can overtake other droplets. The edge of this region forms a narrow strip of extremely high droplet density compared to elsewhere in the flow. A sample simulation is shown in *Figure* 2. This is a simulation of the two-dimensional Navier–Stokes equations[9] which solves for the vorticity everywhere in the flow as a function of time. In this flow, droplets are randomly distributed in accordance with a uniform distribution at the initial time. The location of the droplets at a later time is obtained, and an accurate method for obtaining local number densities of droplets is adopted. High number density is shown in red and low in blue. Two kinds of simulations are shown in the figure. The flow is identical in both. On the left is a simulation where no droplets were placed in the caustics regions at the initial time, and on the right is a simulation where droplets were placed only within the caustics region. The noticeable feature is that droplets which originate well outside the caustics region do not cluster significantly, so the droplet density remains low. The places where the droplet density is high correlate very well with the edge of the caustics region.

In addition, we show in an upcoming paper [15] that even slightly polydisperse populations of droplets (i.e. not all the same size) in the bottleneck size-range, under the influence of a vortex, have sufficiently large relative velocities between particles to lead to significantly higher collision rates. This happens because the ef-

[7] See the pictures in Chapter 6 of Davidson's book [12].

[8] Ignoring viscosity, this induced motion can be described by the Biot–Savart law.

[9] The Navier–Stokes equations, when solved in two dimensions as opposed to three, exclude an effect called 'vortex-stretching', which limits how realistic they are. However, two-dimensional simulations offer a reasonable starting point to test ideas.

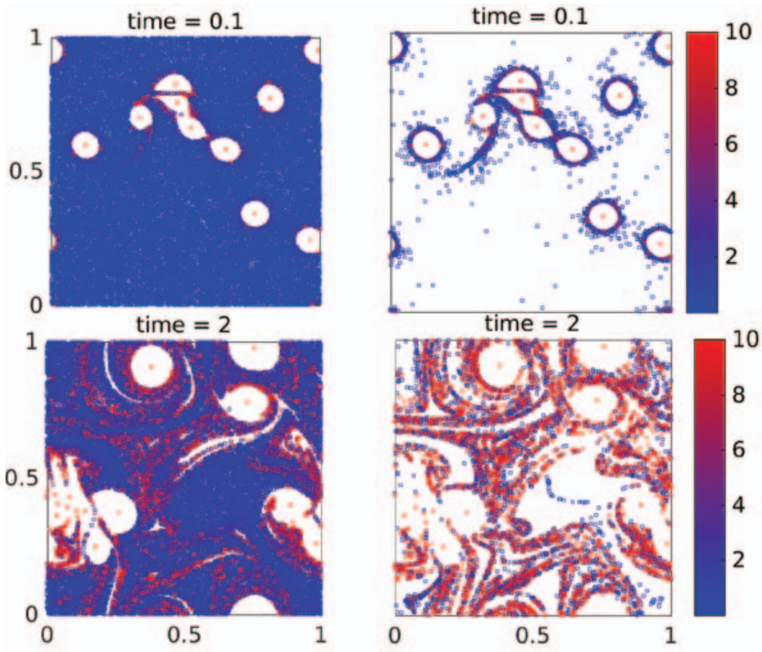

Figure 2. The particle densities are significantly higher for particles that start at the edge of the caustics region [14].

fective 'caustics region' is very large with even small polydispersity, and droplets which originate within the caustics region have a far higher probability of undergoing a coalescence with another droplet than those which originate outside. Moreover, droplets that have undergone at least one coalescence have a far superior chance of repeated collisions and runaway growth[10] in a very short time, even in a dilute suspension. This could therefore provide one way to bridge the bottleneck.

[10]Droplets that are larger, tend to collect smaller droplets at a larger rate (1), growing at an ever-increasing rate; hence the term 'runaway growth'

Droplets of radius larger than 50μ will fall under gravity with sufficient v_{rel} to collide frequently with smaller droplets. A fraction of these collision events will result in the drops coalescing with each other, and the larger drop falling faster. This process can rapidly produce larger and larger drops, until we have rain. The bottleneck from 10μ to 50μ must be bridged either by turbulence (i.e. caustics-induced increase in collision rates; See, [16–18]), or as some researchers suggest, pure luck [11]. We prefer the former explanation, but cannot rule out the 'lucky droplet' route to growth.

Conclusions

We have discussed the basic steps involved in one type of rain-cloud formation. Our discussion pertains to tall clouds. We caution the reader that this is our point of view, and there is no clear proof yet of most of the steps involved.

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Suggested Reading

[1] G S Bhat and R Narasimha,A volumetrically heated jet: large-eddy structure and entrainment characteristics, *J Fluid Mech*., Vol.325, pp 303–330, 1996.

[2] B R Morton, G I Taylor, J S Turner, Turbulent gravitational convection from maintained and instantaneous sources. In *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, Vol. 234, No. 1196, pp. 1–23, 1956, January, The Royal Society.

[3] Geoffrey K Vallis, *Atmospheric and Oceanic Fluid Dynamics: Fundamentals and Large-Scale Circulation*, Cambridge University Press, 2006.

[4] R Narasimha, S S Diwan, S Duvvuri, K R Sreenivas, G S Bhat, Laboratory simulations show diabatic heating drives cumulus-cloud evolution and entrainment, *Proceedings of the National Academy of Sciences*, 108(39), 16164-16169,2011.

[5] D R Sikka, S Gadgil, On the maximum cloud zone and the ITCZ over Indian, longitudes during the southwest monsoon, *Monthly Weather Review*, 108(11), 1840-1853, 1980.

[6] S Gadgil, S Gadgil, The Indian monsoon, GDP and agriculture. *Economic and Political Weekly*, 4887-4895, 2006.

[7] M K Yau, R R Rogers, *A short course in cloud physics*, Elsevier, 1996.

[8] H R Pruppacher, J D Klett, *Microphysics of Clouds and Precipitation*, Reprinted 1980, Springer Science & Business Media, 2012.

[9] Thara V Prabha et al., Microphysics of Premonsoon and Monsoon Clouds as Seen from In Situ Measurements during the Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX), *Journal of the Atmospheric Sciences*, Vol 68, 1882-1901, 2011.

[10] C F Bohren, B A Albrecht, *Atmospheric thermodynamics*, 2000.

[11] M Wilkinson, Large Deviation Analysis of Rapid Onset of Rain Showers, *Physical review letters*, 116(1), 018501, 2016.

[12] P A Davidson, *Turbulence: an introduction for scientists and engineers*, Oxford University Press, 2015.

[13] S Ravichandran, P Deepu, R Govindarajan Clustering of heavy particles in vortical flows: a selective review,*Sadhana*, in press, 2017.

[14] S Ravichandran, R Govindarajan, Caustics and clustering in the vicinity of a vortex, *Physics of Fluids*, 27(3), 033305, 2015.

[15] P Deepu, S Ravichandran, R Govindarajan, Caustics-induced coalescence of small droplets near a vortex, in review.

[16] W. W. Grabowski, L. -P. Wang, (2013), Growth of cloud droplets in a turbulent environment, Annual Review of Fluid Mechanics 45, 293-324.

[17] Y Xue, L P Wang, W W Grabowski, Growth of cloud droplets by turbulent collisioncoalescence, *Journal of the Atmospheric Sciences*, 65(2), 331-356, 2008.

[18] F Y Testik, M K Rahman, First in situ observations of binary raindrop collisions, *Geophysical Research Letters*,2017.

[19] B J Devenish, P Bartello, J -L. Brenguier, L R Collins, W W Grabowski, R H A IJzermans, S P Malinowski, M W Reeks, J C Vassilicos, L -P. Wang, Z. Warhaft, Droplet growth in warm turbulent clouds, *Quarterly Journal of the Royal Meteorological Society* 138, 14011429, 2012.

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