From Heavens to Earth

A Biography of Cumulus Clouds

Deepak Govind Madival

In this article, I discuss the life cycle of cumulus clouds. The events of birth, growth and demise of clouds are discussed in terms of microphysical processes that underlie them. My hope is that the next time you raise your eyes to the sky and see a cloud, it will present itself to your mind's eye as more than a 'white fluffy thing'.

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1. Introduction

Clouds are noble beings, born in the blue heavens and returning to the muddy earth after a brief but vigorous life aloft. Roving the open skies at any given time is an amazing variety of them – short stout clouds, tall towering clouds, wisp-like clouds, flattened clouds, and so on. Their synthetic taxonomy by the reductionist minds is tiresome and of little significance when admiring their varied forms and temperaments. Whence do they come? How do they grow? Why do they perish? So must have wondered even those prehistoric hunter-gatherers when they raised their eyes to the skies. For answers, we must follow the cloud on its journey through its whole life – from birth to death.

One cannot exaggerate the importance of clouds to life and civilization on earth. Imagine an earth on which clouds do not form, and whose water, therefore, lies idle in its oceans, seas, and lakes. How our civilization would be curtailed without the timely supply of freshwater poured out by the clouds! What food could we then grow and where? Greater parts of the earth would be parched deserts. Lakes, ponds and groundwater, once spent would not be replenished. The earth would be fully exposed to the sun (about 60% of earth's face is veiled by clouds today) which would alter its temperature. One may only speculate about the dominant life

Keywords

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form on earth under such harsh conditions.

Clouds are thus essential. But tragedies accompany when they rain too much, too little, or at an unwelcome time. Too little rain causes drought, too much rain a flood. Recall the 2013 Uttarakhand cloudburst and the recent deluge in Kerala and Kodagu which cost us dear in terms of lives and property. And where clouds are unwilling to rain at all, scientists today attempt to intervene and coax them to rain.

In view of the enormous significance of clouds, it is imperative that we learn how they work. Let me not delude you into imagining that every scientific question pertaining to clouds has been answered; on the contrary, there are enough unsolved or poorly understood puzzles pertaining to clouds. However, a broad outline of how clouds form, grow and rain has emerged, and the present article focuses on the same.

I cannot dwell on all types of clouds in this article. If I had to choose one beast of the jungle to describe, I would choose the king lion while cautioning the readers that knowing the lion is not knowing all the varied beasts of the jungle. Similarly, I shall now choose the king among clouds, the 'cumulus', and dedicate this article to it. I hope to pique your curiosity enough so that you will read about other types of clouds too on your own. In the rest of the article, unless mentioned otherwise, by 'cloud' I shall mean 'cumulus cloud'. I must add that 'cumulus' is really a family-name among clouds, and it has further sub-classes; but such labels and classifications do not interest us in this article, whose focus is on the inner workings of a cloud.

2. Birth of a Cloud

A cloud is a vast collection of tiny liquid water droplets.

Being born is no more than acquiring an identity, a label. Whenever a vast number of water droplets aggregate in the skies, packed close enough (but not touching and melding into each other) to form a single large identifiable body, a cloud is born. Every cloud is thus a collection of tiny water droplets (*Figure* 1) as a human body is a collection of tiny cells. I cannot answer if you ask me

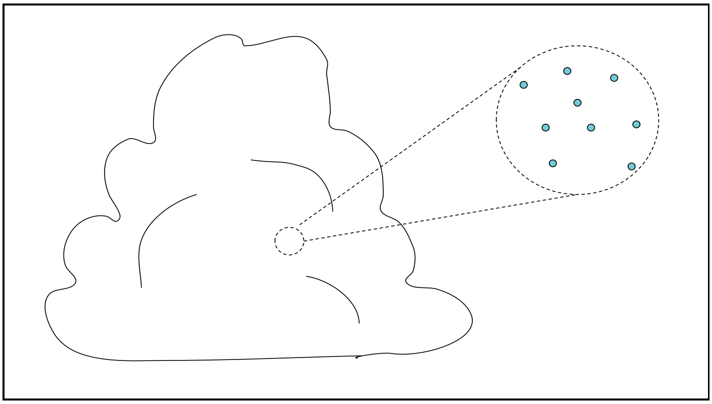

Figure 1. When you zoom into a cloud, you see that it is a vast collection of tiny liquid water droplets.

how many droplets must gather together before their aggregate may be called a cloud; it is like asking how many cells must the embryo have before it is considered a human being.

A newborn cloud is made of water droplets of size less than about 10 μm, which is at least ten times smaller than the thickness of a strand of your hair. A cloud may seem densely packed to you while looking up from the earth. But if you shrink down to the size of the droplets and wander around inside a cloud, it begins to seem more like a sparsely populated village than an overcrowded city. The average spacing between cloud droplets can be 1 mm or more, which is a hundred times the droplet size. From their viewpoint, a cloud is a large, loosely-knit, group of nomadic droplets wandering the vast prairies of the blue sky, going where turbulent winds of destiny carry them.

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Yet one wonders how cloud-droplets form and that too at such great heights above the earth? In other words, how is a cloud born? Water can exist in liquid as well as vaporous (gaseous) form. Mother Nature has decreed that for a given temperature of water vapor (same as the temperature of air of which water vapor is but a part) there is a threshold for the quantity of water vapor per unit volume of space which cannot be exceeded. The law is that higher the temperature, greater is this threshold for the quantity of water vapor per unit volume of space. At 20°C the threshold is about 15 gram of water vapor per cubic meter of space, while at 0°C the threshold reduces to about 5 gram of water vapor per cubic meter of space.

If the actual quantity of water vapor in the air were to exceed this threshold then all the water vapor in excess of the threshold would forthwith condense into liquid form. Air is said to be 'saturated' if the quantity of water vapor in it is exactly at its threshold value (corresponding to whatever is the air temperature). A nice analogy is a glass filled with some liquid. You can only fill the glass up to its brim and if you pour extra, the excess liquid spills out. The height of the glass is analogous to the temperature of water vapor and the liquid is analogous to water vapor itself[1]. The glass filled up to its brim is analogous to saturated air. Further, air is said to be 'supersaturated' or 'undersaturated' accordingly as its water vapor content is above or below the threshold value. Supersaturated air always attempts to give up its excess vapor (by converting the excess vapor to liquid state) and thus return to saturated state. On the contrary, undersaturated air attempts to fill itself up with water vapor by evaporating away any liquid water in its contact so that it may reach the saturated state. Undersaturated air is analogous to a partially filled glass of liquid; supersaturated air, unfortunately, does not beget a simple analogy.

[1]The actual relation between temperature and water vapor concentration is highly nonlinear.

Nearly half of the sun's radiation incident on earth is reflected or scattered by various agencies in the atmosphere such as dust particles, other clouds, the air molecules, and finally by the earth itself[2]. A small proportion of the incident solar radiation is absorbed by the earth (and an even smaller proportion is absorbed by the atmospheric air). This heats up the earth, which in its turn heats up the air in contact with it, which then begins to rise towards the sky[3]. The rising air is undersaturated (think of a half-filled glass) when it begins. Since temperature decreases with altitude (by $\sim 7^{o}$C for every kilometer of ascent) the rising air is continuously cooling down (think of the height of glass decreasing, with the quantity of liquid in it unaltered). At some altitude, usually about 2 km above earth, the temperature of rising air falls so low that air becomes supersaturated and water vapor begins to condense out (think of height of glass reducing below the liquid level in it, so the excess liquid must spill out); at this altitude lies

[2]Reflection is high from ice-surfaces and deserts.

[3]Heating of air reduces its density making it buoyant.

the base of the cloud.

The excess water vapor in the supersaturated air, however, needs a surface on which to condense and the ever-present dust particles in air provide it, and thus cloud droplets are formed on them. In the absence of dust particles, it is not impossible for a large number of water vapor molecules to perchance stick together (by random collisions) to form a viable droplet; but for this event to become likely over a realistic time duration, requires a very high supersaturation which is not found in clouds, and therefore this mechanism of droplet formation is ruled out. Further, more the dust particles in the air more the droplets that are formed. A cloud forming in the pristine air above oceans can have a few hundred cloud droplets per cc of air, while a cloud forming in polluted air above an industrial area can have a few thousand cloud droplets per cc of air. We may note that since only so much mass of excess water vapor can condense out of the supersaturated air, greater the number of dust particles and therefore more the droplets formed, more thinly is the condensate spread out among them and therefore smaller is their average size.

If the water vapor content of air exceeds the maximum threshold then it condenses onto dust particles available in the air.

3. A Digression: Why the Threshold for Water Vapor?

The threshold for water vapor mentioned in the previous section appears mysterious. Why should there be a threshold at all? Why cannot there be an unlimited quantity of water vapor in a unit volume of air? If you are imagining air to be some sort of sponge which can absorb only so much water vapor, then know at the outset that this analogy is misconceived. The threshold exists even when there is no air (by 'air' I mean the aggregate of oxygen, nitrogen, and other trace-gases excluding water vapor). To make sense of the threshold, we must zoom into the molecular level.

The three phases of matter – solids, liquids, and gases – are distinguished only by the mobility of molecules. Ice, liquid water, and water vapor all contain the same water molecules (chemical formula: H_2O, which is two hydrogen atoms bonded to one oxygen atom), in the sense that if you swap (say) a molecule of liquid

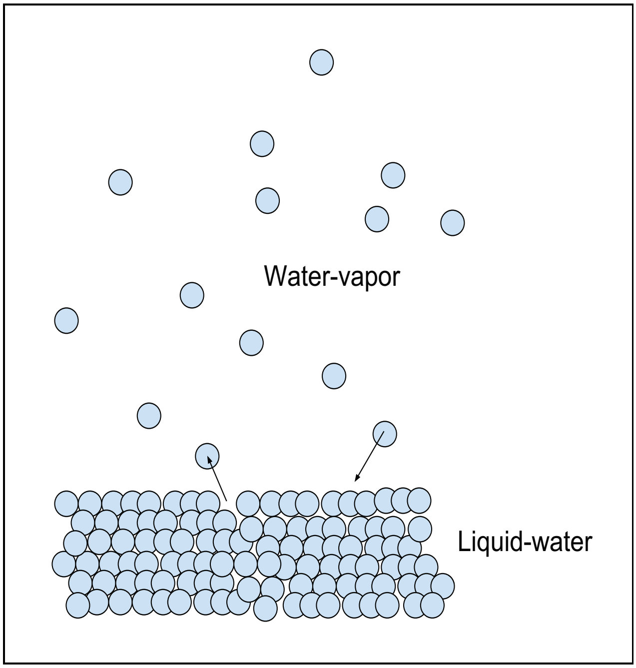

Figure 2. Interface between liquid water and water vapor. Filled circles are H_2O molecules. Arrows indicate the direction of motion.

water with a molecule of water vapor, nothing changes. However, in the liquid state, the H_2O molecules are bonded together more and are, therefore, less mobile than H_2O molecules in the vapor phase which simply whizz around in space oblivious of each other (except when they collide). The H_2O molecules in solid ice are entirely immobile and firmly locked into place.

Now, imagine a liquid body of water in contact with water vapor (for simplicity suppose there are no other gases). The liquid water body and vapor are continuously exchanging H_2O molecules with each other (*Figure* 2). While on the one hand, one H_2O molecule in vapor perchance hits the liquid surface and is captured, becoming part of liquid water, on the other, a H_2O molecule breaks free of the liquid water body (due to thermal agitation) and leaps out into the vapor to become a part of it. Even over a short one-second duration, a stupendous number of H_2O molecules cross, in both directions, the border separating liquid and vapor. If more number of molecules enter the liquid body than escape from it per unit time, then the mass of the liquid body increases; in the inverse situation (outgoing more than incoming), the mass of the liquid body decreases. If the number of molecules arriving equals those leaving (per unit time), then the mass of the liquid body shall remain constant; the liquid and its vapor are then said to be in equilibrium with each other.

What determines the rate at which molecules enter or leave the liquid body? Let us look at a H_2O molecule which is part of the liquid surface. To leap off into the vapor phase, it must break the chemical bonds with its neighbors, for which it needs energy. Now, higher temperature implies more vigorous motion of molecules; as temperature increases, not only does the average kinetic energy of a H_2O molecule increase but at any given time instant, the molecules possess more widely differing kinetic energies (compared to average). Those molecules fortunate enough to acquire kinetic energy high enough to break the bonds with their neighbors fly away from the liquid body. Hence, the rate at which molecules leave the liquid body increases with temperature.

Let us now look at a H_2O molecule in the vapor region. This freely roaming vagabond has no bonds to break. The rate at which H_2O molecules from the vapor hit the liquid surface increases with the increase in the concentration of H_2O molecules in the vapor. This is because more the concentration of H_2O molecules in the vapor phase, more of them perchance hit the liquid surface (per unit time). The lesson being, the rate at which molecules enter the liquid body increases with the concentration of H_2O molecules in the vapor.

Now, you may deduce why water vapor quantity has a threshold. Consider liquid water in equilibrium with its vapor, i.e. number of H_2O molecules leaving the liquid body equals that entering it. If now by some means, you inject more H_2O molecules into the vapor (resulting in super-saturation), the number of H_2O molecules from the vapor phase hitting the liquid surface increases; the number of molecules leaving the liquid body, however, remains the same (because the temperature hasn't changed). The mass of the liquid body, therefore, increases, which is what we call the 'condensation' of vapor. Condensation continues until the concentration of H_2O molecules in the vapor phase reduces back to its equilibrium value. This explains the threshold.

You may go ahead and explain other cases too. For example, if you increase the temperature of the liquid body, the rate at which molecules leave it increases, resulting in a decreased mass of the liquid body – a process called the 'evaporation' of liquid. Whether evaporation will stop at some point or will continue until no liquid remains, depends on whether there is a way to retain the H_2O molecules that escape from the liquid body into the vapor phase. For liquid inside a closed container, the escaping H_2O molecules are retained within the container. In this case, the concentration of H_2O molecules in the vapor inside the container increases as the liquid evaporates, which in turn increases the rate at which H_2O molecules from the vapor hit the liquid surface. Evaporation stops when the rate at which H_2O molecules leaving and entering the liquid body balances again (at a higher value this time). Similarly, you may argue why decreasing the temperature of the liquid body results in vapor condensation.

4. Childhood and Youth

Clouds grow by buoyant convection, which is propelled by the heat released during the condensation of water vapor.

A cloud is born of the moist air rising from the earth which is heated by the sun. Once the droplets begin to form in the rising moist air parcel above a certain height from the earth, the newborn cloud immediately enters a vigorous growth cycle. The reason is the heat released when water vapor condenses; it heats up the moist air parcel which becomes buoyant and is compelled to rise, cooling further upon ascent, condensing out water again accompanied by heat release, further heating up the moist air parcel . . . and so on in a self-perpetuating cycle. This vigorous youthful growth cannot, of course, continue forever. The moist air parcel may eventually run out of water vapor to form a significant number of droplets as it mixes with the drier ambient air as it ascends, which in turn serves to dilute its water vapor content. The growing cloud may also bump its proud head against an invisible ceiling in the upper atmosphere[4], appropriately named 'tropopause', above which lies the stratospheric region in which temperature in-

[4] Its height varies from ~10 km at poles to ~18 km at equator.

creases with height instead of decreasing. Due to this, the cloud is unable to penetrate it and begins spreading sideways (aided by strong winds at that high altitude) instead of growing vertically. Thus clouds can be as dwarf as 1–2 km or as tall as 12–13 km.

Not only does the cloud grow its bulk by creating more and more droplets, the citizens of the cloud, the tiny droplets, grow in tandem too. Initially, these little suckling droplets grow by feeding on water vapor in the air that surrounds them; of course, they must be fortunate enough to be surrounded by supersaturated air. If the air surrounding them is undersaturated, then the droplets will instead diminish in size by evaporating away. Of course, nothing is wasted by Mother Nature; while droplets that are growing suck out water vapor from the air surrounding them, droplets that diminish increase the water vapor content in the air surrounding them, which may ultimately feed some other droplet in the cloud.

In their lifetime, droplets don't remain ensconced in one air parcel but are thrown hither and thither by violent turbulent winds, forcing all the droplets to experience varied conditions of air, both supersaturated and undersaturated. If a cloud-droplet could speak, it would narrate its survivor's tale thus: "When I was born I was growing well enough, but next instant I was thrown into an air parcel in which I began diminishing. Just as I feared total disappearance I was again perchance thrown into another air parcel in which fortunately I could grow again, but then again I was....I have been into air parcels that were already populated by many droplets which meant lots of mouths to feed and so I could not get enough water vapor for myself, and I have also been into air parcels so isolated that all the water vapor in it was my own....I have met other droplets during my turbulent journey who weren't lucky enough to survive as long as I have...." Even if all the droplets were to begin identical, their fate, guided by turbulent winds cause them to grow differently from each other, so that sometime later (probably a few minutes) the survivors shall have grown to a variety of sizes. They, like us, are a product of their varied individual histories.

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Growing through water vapor condensation serves the cloud droplets

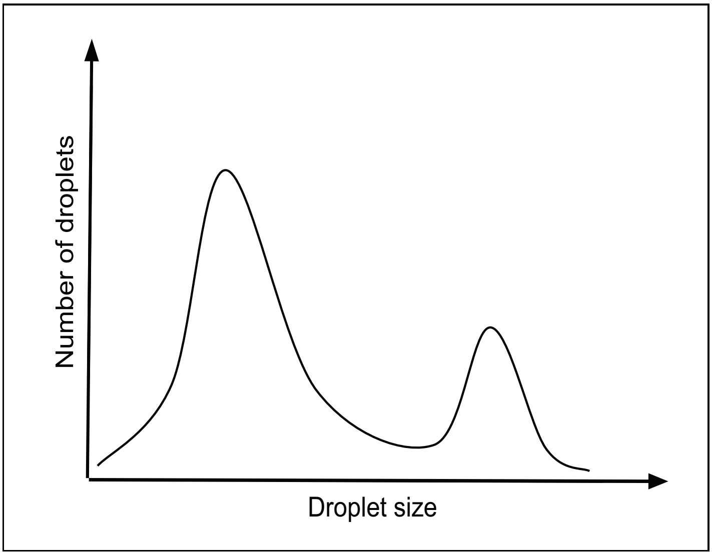

Figure 3. Double-hump distribution of cloud droplet size. The hump at the larger-size end is due to growth by collision-and-coalescence. [See Rogers and Yau in Suggested Reading.]

Growing through water vapor condensation serves the cloud droplets during its childhood but not beyond. The growth rate of a droplet by condensation is inversely related to its size so that larger a droplet, slower is its growth thereafter.

during its childhood but not beyond. The growth rate of a droplet by condensation is inversely related to its size so that larger a droplet, slower is its growth thereafter. So slow in fact that for a droplet of size about 40 μm, growth by condensation is practically nil. The young cloud hereafter depends on a new mode of faster growth, none other than simple collision-and-coalescence, i.e. cloud droplets collide and become one creating a new bigger drop in their stead. Just as during condensational growth, turbulent winds orchestrate collisions among droplets as well, by throwing droplets around pell-mell, causing them to collide perchance. During the initial phase of growth by condensation, cloud droplets are small and of nearly identical size, so (despite turbulence) the likelihood of their collision is small. However, condensational growth as we have seen, creates droplets of varied sizes including a small proportion of large droplets (up to $\sim$40 μm). This inequality among droplets sets the course for collisions among them because they move differently when impelled by turbulent winds. For example, if droplets are thrown out by a rotating air parcel, then due to the difference in their speeds (because of their different sizes), the droplets may collide.

Growth by collision-and-coalescence is vigorous and continues until a sizeable proportion of the cloud droplets reach a size of

60–80 μm. At this stage, the inequality among droplets has worsened. Now, there is a large community of small droplets centered about 20–30 μm, and a second large-enough community of droplets centered about 60–80 μm (they are interspersed among each other and not spatially segregated). If a census of droplets were performed and the number of droplets of each size was plotted on paper, the plot would be double-humped (*Figure* 3). However, I must add that this simple picture of growth remains debatable.

5. A Digression: Turbulent Winds

To not discuss turbulent winds, the sire of cloud droplets, would be remiss of me. Not just the winds but many other flows of the world are turbulent – flow in rivers and oceans, our breathing, flow inside an engine, convection in sun, etc. Common to all turbulent flows is their seemingly disordered motion. But this begs the question: What then is to be considered 'ordered motion'? Is it motion in straight lines, circles, ellipses, and such platonic patterns? Mother Nature cares not a whit about platonic patterns or, for that matter, anything else simply because it pleases humans. So thinking of turbulence as disordered motion is vaguely intuitive but let us not rely on it.

A more satisfactory feel for turbulent flows may be had by thinking in terms of 'mixing'. Suppose you take a bowl of water and gently pour some warm oil on top of the water. Not being miscible, warm oil floats atop the colder water. If you wait, the temperature of oil and water eventually equalize. However, experience shows that if you were to vigorously stir it instead, temperature equalizes more quickly. What does mixing (due to stirring in this case) do?

In the unstirred bowl, heat flows from the warm oil to the colder water through conduction, much as heat flows through the end of a metal spoon immersed in hot tea to your fingertips. Also, heat must flow through the area of contact between oil and water which remains fixed. Stirring increases this area of contact between oil and water by interspersing them, thus facilitating more heat transfer by conduction between them. This is manifested by quicker equalization of temperature. In general, mixing brings fluid parcels of disparate physical properties into contact, thus facilitating a quicker exchange of whatever can be exchanged between those fluid parcels.

What can be exchanged between fluid parcels thus brought into contact? The answer – heat, species, and momentum.

What can be exchanged between fluid parcels thus brought into contact? The answer – heat, species, and momentum. If temperature differs between these fluid parcels, then heat flows between them (from higher to lower temperature). If the concentration of a chemical species, say water vapor, differs between these parcels, then the species flows between them (from higher to lower concentration). The same applies to momentum, whose vector character renders its description more complicated than is suitable for this article. What besides stirring can achieve vigorous mixing motion of fluids? Any force of sufficient magnitude that acts on fluid parcels: buoyancy due to density difference (think of incense smoke), mechanically applied pressure (for example, using a pump), electromagnetic forces (prominent in sun's atmosphere), etc., can have the same effect.

You may think of 'turbulent flow' as a label for vigorous mixing motion of fluids (whatever be its cause). Those flows which do not exhibit vigorous mixing no matter how seemingly complicated, are called 'laminar flows'. In nature, laminar flows are an exception and turbulent flows the rule. So, if a flow looks complicated, it is likely turbulent. In clouds, buoyancy force by virtue of density differences (due to temperature and water vapor concentration differences) is the chief cause of turbulence.

Suppose you froze a cloud in action, then took a sensitive thermometer and measured the temperature along a straight line inside the cloud. As evidence of mixing of the air parcels of varied temperatures by turbulent winds, you will see that the temperature reading varies wildly along the straight line, plummeting and rising repeatedly. In other words, the temperature plot along that line looks jagged (*Figure* 4). In a strongly turbulent cloud, this jaggedness may appear even over such a short distance of mea-

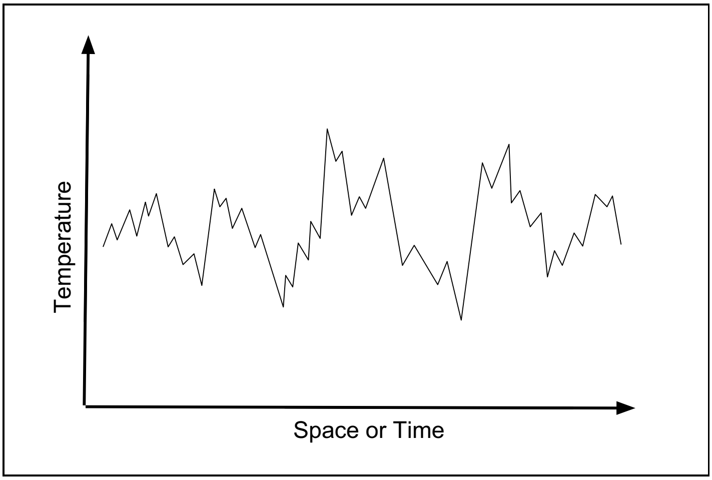

Figure 4. Temperature measured along a spatial direction (at fixed time) or along time (at a fixed point) displays wide fluctuations. This is true for any physical quantity other than temperature, such as pressure, density, etc.

surement as 1 cm. How thoroughly mixed must the cloud be! And not just temperature, but pressure, water vapor concentration and what-have-you will show such jagged variation throughout the cloud. Same is the case if you measured (say) the temperature at a fixed point inside the cloud over time; the plot of temperature with time looks jagged and may remain jagged even over such a short duration of measurement as 10 seconds. Now, imagine a droplet in the midst of such turbulence. When propelled along a line by turbulent winds, it experiences varied conditions even over a short distance of travel; even if it were to stay put in one place (it can't) the droplet cannot evade experiencing varied conditions even over a short duration of repose. In summary, cloud droplets are doomed to experience varied conditions of water vapor concentration and temperature during their lifetime. We have seen earlier how this leads to a variety of droplet sizes during the first phase of growth by condensation, this variety being essential for the success of next phase of growth by collision-and-coalescence.

Cloud droplets are doomed to experience varied conditions of water vapor concentration and temperature during their lifetime, and this leads to a variety of droplet sizes.

This concludes our brief acquaintance with turbulence, a deep and enticing subject in itself. Next, we move on to the last phase of growth of clouds in which turbulence does not play a dominating role; it is as if the cloud now defies the turbulent winds and sets on its own course of development. Let me end this section by addressing a curious question. Since droplets are made of liquid water, which is thousand times denser than air, why don't they simply fall down to earth as soon as they form? How can they float in the sky long enough for a cloud to form and sustain itself? Water droplets do indeed fall towards earth, but with small velocities[5]; a 10 μm water droplet in the air falls at ~1 mm/s. To reach the earth, they must cover a distance of few kilometers, which takes long. During this long journey, several things may happen to an earthward bound droplet; it could evaporate and vanish midway because the air beneath the cloud base is undersaturated[6], or the relentless turbulent winds may scoop it up and throw it back into the cloud.

[5] For droplets of diameter up to 60 μm, settling velocity is proportional to (diameter)^2.

[6] Smaller the droplet, faster it evaporates.

6. Old Age and Demise

Small droplets are helpless in that they are thrown around pell-mell by turbulent winds. But as droplets grow bigger, their sluggishness begins to counter the force of turbulent winds. Corpulent droplets of size ~ 80 μm cannot be strong-armed effectively by turbulent winds anymore; these droplets now begin to fall towards earth under the influence of its gravity.

While falling, these large droplets collide and coalesce with others that cross their path and thus keep growing. In this manner, falling droplets can grow to a size of 1 mm or more. When these droplets hit earth in large numbers, lo we have rain! Large droplets have much higher settling velocity and take less time to reach earth; of course, the initial size of these drops must be large enough so that they do not evaporate and vanish midway during their journey.

A stupendous growth story has it been indeed, beginning from a size of less than 10 μm and ending up with a size of more than 1 mm, a hundred-fold growth in girth, or equivalently a million-fold growth in volume[7]. Further, observation of clouds reveals that cloud-droplets grow so much over an average duration of 30–40 minutes, about the duration of a classroom lecture. That is fast!

[7] Because volume is proportional to (size)^3.

Pouring out as rain is the cloud's rite of passage into afterlife[8]. The cloud empties out and vanishes away. Few droplets that may remain in the sky after the cloud has rained out usually evaporate

[8] Not every cloud rains out, however.

away, and the demise of the cloud is complete. The rainwater then flows on the earth's bosom until it evaporates again and becomes another cloud. Thus the wheel of life continues to roll: what is enthroned in blue heavens is pulled down into the lowly mud of earth, and then is raised to the top again, and so on eternally[9].

[9]To be precise, only until our Sun lasts.

7. Miscellaneous Matters

As mentioned in the introduction, this article is about cumulus clouds, born of air rising from the heated earth and waterbodies on it. There are other ways too for clouds to be born. For example, traveling wind that comes upon a mountain is forced to climb up its face, cooling down as it ascends until water vapor begins to condense out of it ('orographic clouds'). The core idea, you must have realized, is that air must be somehow cooled down sufficiently for the water vapor to condense out, usually achieved by lifting it to higher altitudes by various means. Here's another such mechanism: when two fronts (or masses) of moving air, one warm and another cold, meet each other, the less dense warm air is forced to ascend the heavier cold air-mass, which cools it down until water vapor begins to condense out of it. However, there is also a way for air to cool down without ascending to higher altitudes. Fog can form of an air-mass on the ground which cools down sufficiently during night-time; fog is that rare humble cloud which is born on the ground.

A cloud is not always made of liquid water droplets. If a cloud grows sufficiently tall, then the cloud top may experience subfreezing temperatures giving rise to (tiny) ice crystals instead of liquid water droplets. Sometimes, such a cloud may rain out leaving only its uppermost part made of ice crystals high up in the sky. These usually appear like strokes of paintbrush upon the canvas of sky ('cirrus clouds').

Cumulus clouds look like a heap of piled up cotton (see the shape of the cloud in *Figure* 1 as it is usually drawn). Its girth decreases with height because the rising cloudy air (i.e. air containing water droplets) progressively mixes with the undersaturated ambient atmospheric air. This mixing causes depletion of cloud droplets, beginning from its edges and moving inwards towards its core. In other words, ambient atmospheric air eats into the cloud as it grows, and therefore the cloud's girth progressively reduces as it becomes taller.

We have seen how rising air parcel precipitates out water droplets to form a cloud. However, the cloud does not exclusively contain rising air currents. There are downward drafts too inside the cloud when the top of the cloud cools, and cloudy air at the top becomes denser and thus sinks.

Finally, not all rains reach earth; such rains are called 'Virga'. In such rains, raindrops completely evaporate midway during their journey towards earth. This may happen when the cloud forms at a very high altitude so that the raindrops must travel a long distance, a journey which they may not survive[10]. This can also happen if the air underneath the cloud is so severely undersaturated (for example, over a desert) that cloud droplets completely evaporate even over their usual distance of journey towards earth.

[10]Recall that air beneath the cloud base is always undersaturated and so the cloud droplets inevitably begin evaporating when they leave the cloud.

8. Parting Thoughts

In this article, I have barely scratched the surface of the physics of clouds, which is an important and lively branch of research and debate all over the world. I hope it inspires you to dig into the phenomenon of clouds with greater interest.

To summarize the article, we learned about cumulus clouds, formed when warm air rises from the earth and cools down as it ascends to higher altitudes, precipitating out water droplets beyond a certain altitude (~2 km). Initially, cloud droplets, which are less than 10 μm in size, grow by the condensation of water vapor. They experience diverse conditions as they are thrown around by turbulent winds, resulting in droplets of various sizes including a small fraction of droplets as large as 30–40 μm. From this point, collision-and-coalescence among droplets becomes the dominant mechanism of growth rather than the (much) slower condensational growth. The cloud droplets which thus grow to about 70–

80 μm size are less influenced by turbulent winds and begin to settle under gravity, colliding and coalescing with droplets that perchance cross their path. In this fashion, they may grow to the size of a few millimeters. These large drops hit earth as rain, and thus a cloud's life is complete.

A science article is not worth its salt if it does not inform the reader of at least a few interesting open questions in its field. The content of this article is neat and well-arranged because I have presented only the broad outlines of the subject. The scene becomes chaotic if one descends into the underworld of details; here, new theories and speculations are floated, which are then debated, objected to, refuted, or (in the more fortunate case) tentatively accepted.

Cloud scientists find the rapid growth of cloud droplets quite puzzling. While they accept that collision-and-coalescence induced by turbulent winds must be the accelerating factor, the question "How exactly do turbulent winds enhance the collision rate between cloud droplets?" remains a matter of debate. Some suggest that turbulent winds cause bunching together of the droplets (instead of being distributed approximately uniformly over space) which increases the chances of collision among them. Some others suggest that cloud droplets are shot out from the turbulent regions (as if from a sling) resulting in higher collision rates, and bunching of droplets is not really necessary. You may wish to exercise your mind to find a new mechanism by which collision rate among cloud droplets is enhanced.

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For collision among droplets to become the primary mechanism of growth, a wide variety of droplet sizes are necessary (with at least a small fraction of droplets as large as 30–40 μm), and these have to be produced quickly. Much effort is being spent to answer the question "How exactly do turbulent winds help growth due to condensation – whose natural tendency is to produce a narrow distribution – to actually produce cloud droplets of varied sizes in a short duration (say less than 10 minutes)?"

Notice that turbulent winds feature prominently in both questions.

Without turbulence, clouds would certainly not rain out in a short duration (less than an hour), and the average lifespan of clouds would be longer (a day perhaps). However, turbulent flows constitute a difficult problem. The behavior of turbulent flows cannot be usefully predicted even in simple man-made situations, let alone that in the atmosphere or inside clouds. Whenever turbulence makes its appearance in a physical phenomenon, you are guaranteed tough questions that will linger a long time.

There are many other deep and interesting questions pertaining to clouds, but they are outside the scope of this article. Let us stop here, walk out, and watch the glorious clouds!

Suggested Reading

[1] C F Bohren, *Clouds in a Glass of Beer: Simple Experiments in Atmospheric Physics*, Dover Publications, 2001.

[2] R R Rogers and M K Yau, *A Short Course in Cloud Physics*, Butterworth-Heinemann, 1989.

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