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CAPE - A link amid thermodynamics and microphysics for the occurrence of severe thunderstorms

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सार – इस शोध–पत्र का उद्देश्य कोलकाता (22°32′, 88°20′) में मानसून पूर्व ऋतु (अप्रैल–मई) के दौरान गर्ज के साथ आने वाले भीषण तूफानों की उत्पत्ति और विकास में सहायक मेघ की सूक्ष्म भौतिकीय प्रक्रियाओं की जाँच करना है। इस अध्ययन से यह पता चला है कि कोलकाता में मानसून–पूर्व ऋतु के दौरान गर्ज के साथ आने वाले भीषण तूफानों के दौरान तापगतिकीय, गतिकीय, मेघ की सूक्ष्म भौतिकी और बिजली चकमने को श्रृंखलाबद्ध करने में संवहनीय उपलब्ध विभव ऊर्जा (सी. ए. पी. ई.) सहायक है। इस अध्ययन से प्राप्त हुए परिणामों से यह पता चला है कि कोलकाता में संवहनीय उपलब्ध विभव ऊर्जा 1000 जूल्स प्रति कि. ग्रा. के भीतर प्रबल पाई गई जो मुक्त संवहन स्तर (एल. एफ. सी.) से ऊपर निर्धारित दाब स्तरों के भीतर पाई गई और वायु की अपड्राफ्ट गति के सदृश मान निष्प्रभावी उत्प्लावकता स्तर (एल. एन. बी.) में लगभग 30 - 50 मी./ सेकेंड पाए गए। इस अध्ययन से यह भी पता चला है कि 5 मि. मी. तक के व्यास के आकार की बूँदे स्थिर रह सकती है जिसके बाद आकार बढ़ने के कारण बूँदें टूट जाती हैं। जब बूँद की त्रिज्या 2.5 मि. मी. से 3 मि. मी. की परिधि में होती है तब बूँदों का टूटना शुरू हो जाता है और 3 मि. मी. से 5 मि. मी. की परिधि में बूँदों के टूटने की संभावना अधिक होती है क्योकि इस स्थिति में बूँदों के लगातार टूटने की कारण उनका जीवनकाल बहुत छोटा हो जाता है।

ABSTRACT. The aim of the present paper is to view the cloud microphysical processes entailed in the genesis and the development of the severe thunderstorms of pre-monsoon season (April - May) over Kolkata (22°32', 88°20'). The study shows that Convective Available Potential Energy (CAPE) is instrumental in establishing a linkage among thermodynamics, dynamics, cloud microphysics, and lightning during severe thunderstorm of pre monsoon season over Kolkata. The results of the present study reveal that for the thunderstorms reported over Kolkata, CAPE are found to be predominantly within 1000 joules per kgs within the prescribed pressure levels above the Level of Free Convection (LFC) and the corresponding values of the updraft speeds of the air are found to be nearly 30 - 50 m/s at the Level of Neutral Buoyancy (LNB). The study also depicts that the drops may grow up to the size of 5mm in diameter stably, beyond which, they tend to breakup due to the large drop instability. The breakup or splitting is observed to initiate when the drop radius is within the range of 2.5mm to 3mm and the breakup is most likely within the range of 3mm to 5mm because at this stage the lifetime of the drops are short due to the spontaneous breakup.

Key words – CAPE, Updraft speed and breakup of droplets, Pre-monsoon thunderstorms.

1. Introduction

Cloud microphysics is the branch of atmospheric sciences concerned with many particles that make up the cloud. Related to the cloud as a whole the individual particles are very small and so exist on a micro scale, that is, over distances from the fraction of a micrometer to several centimeters. The micro scale structure of the cloud, the specifications of the number, concentrations, sizes, shapes and the phases of the various particles are important to the behavior and the lifetime of the cloud. The ability of the cloud to produce rain or snow, to generate lightning and alter the radiation balances of the earth, for instances, stems in the large part of their individual microstructures. The cloud physicists of atmospheric sciences discipline attempt to characterize the diverse microstructure of the atmospheric cloud and to realize phenomena that cause them to change with time. Cloud typically forms in response to the changes in atmospheric condition on the scales much larger than the particles itself, indeed much larger than the cloud itself, most commonly up ward motion of the moist air driven by the synoptic scale disturbances or, convection, (Houze, 1989) causing decrease in the local pressure and the temperature that lowers the equilibrium vapor pressure of the liquid and solid phases of the water. Excess vapor that amounts above the equilibrium value develop in the rough proportions to the magnitude of the updraft speed. This state of disequilibria is gradually revealed as the vapor condenses over suitable aerosol particles to form liquid and solid ice particles of the cloud. A cloud especially at the early stages of the formation often exhibits property of the colloidal systems, a suspension of the tiny particles that follows the air and interacts only weekly with one another. Where as individual aqueous particles may form and grow and subsequently disappear. The system, as a whole remains micro physically stable for a time and well characterized in terms of number, concentration of liquid drop and ice particles. The discipline of cloud microphysics helps to understand specific mechanism needed for such colloidal stability and to form precipitation. Typically for the thundercloud of high vertical extent, the cloud is normally in the mixed phase (0° C to - 40° C). In this mixed phase both the liquid and solid phase of water are present. (–) 40 degree Celsius is practically the lower limit for the liquid water to exist in a metastable state.

2. Theoretical aspects & methodology

2.1. *Role of Convective Available Potential Energy (CAPE)*

Convective Available Potential Energy (CAPE) represents the maximum limit of the energy, which the parcel can extract from the environment once it becomes buoyant (Chappell and Smith, 1975).

CAPE is mathematically represented as follows

$$\mathrm{CAPE}(Z) = \int_{\mathrm{LFC}}^{Z} \left[\frac{\left(T_{\mathrm{parcel}} - T_{\mathrm{enviornment}}\right)}{/T_{\mathrm{enviornment}}} \right] \mathrm{g}\,\mathrm{d}z \qquad (1)$$

Where

T_{parcel} = Temperature of the parcel.

$T_{\mathrm{environment}}$ = Temperature of the environment.

g = Acceleration due to gravity.

CAPE is one of the most important aspects among thermodynamics, thunderstorm dynamics, cloud microphysics, and lightning. CAPE continues to provide the upper bound for the kinetic energy of the updraft speed. It can therefore be used as the mechanism to study the microphysical aspects of severe thunderstorms. Large CAPE is generally found to be associated with such thunderstorms. CAPE can be computed at various pressure levels up to the mid level in the cloud to evaluate the corresponding updraft speed and the cloud droplet sizes at different heights.

2.2. *Computation of maximum updraft speed at any level*

Conditional instability is a mechanism by which maximum thunderstorms are formed. Conditional instability forces the air to rise up with a certain velocity, which is normally called the updraft velocity. The mass of 1 kg of air having updraft speed of $W(z)$ at any level acquires the kinetic energy of ½$[W(z)]^2$ Joule per kg. CAPE, which is the energy extracted by the parcel from the environment is supposed to provide the buoyant energy to the parcel (Williams, 1995). Thus the kinetic energy must be exactly matched with CAPE (J/kg), that is,

$$1/2[W(z)]^2 = \mathrm{CAPE}$$

$$W(z) = \sqrt{2\mathrm{CAPE}} \qquad (2)$$

As CAPE can be measured, the updraft speed of the air parcel can also be measured. CAPE is measured from LFC to any height; the value of CAPE thus always increases with the height. It is thus observed that with rise in the altitude the value of the updraft speed goes on increasing. In the present study the updraft speed of the air is considered to be of much importance because the particles/drops of ice/water often attains the air velocity. According to the parcel theory, all particles within the parcel attain the updraft velocity. Area covered by the positive energy or CAPE measures the amount of energy acquired by the parcel. Thus, shape of CAPE is extremely important in measuring the amount of energy involved in the system. The updraft speed that directly depends on CAPE is also affected by the shape of CAPE.

2.3. *Computation of terminal velocity & size of the cloud particles*

The drag force exerted by a viscous fluid on a sphere of the radius r is given by

$$F_R = \Pi / 2r^2 u^2 \lambda C_{\mathrm{D}} \qquad (3)$$

Where

u → Velocity of the sphere relative to the fluid

λ → Fluid density

C_{D} → Drag coefficient characterizing the flow.

In terms of the Reynolds number

$$\mathrm{Re} = 2\lambda ur/\mu \qquad (4)$$

Where

μ → Dynamic viscosity of the fluid

Equation (3) can thus be expressed as

$$F_R = 6\Pi\mu ru\left(\frac{C_D \,\mathrm{Re}}{24}\right) \quad (5)$$

The gravitational forces on the sphere is given by

$$F_G = \frac{4\Pi r^3 g(\lambda_L - \lambda)}{3} \quad (6)$$

Where

λ_L → Density of the sphere

λ → Density of the fluid

The density of the fluid is the density of the air in the present situation and the value is much lower than that of the density of the sphere. We can thus have

$$F_G = \frac{4\Pi r^3 \lambda_L g}{3} \quad (7)$$

The drop attains the terminal fall speeds when the drag forces on the sphere become equal to the gravitational forces. For such situations we have;

$$u^2 = \frac{8rg\lambda_L}{3\lambda C_D}$$

$$u \frac{\frac{2r^2 g\lambda_L}{9}}{\mu(C_D \mathrm{Re}/24)} \quad (8)$$

In case of lower Reynolds number, we obtain;

C_D Re/24 = 1

$$u = \frac{2r^2 g\lambda_L}{9\mu}$$

$$u = k_1 r^2 \quad (9)$$

Where

$k_1 = 1.19 \times 10^6$ cm^{-1} sec^{-1}

For sufficiently high Reynolds number, C_D is independent of Re and often have the value of 0.45. Thus, Equation (9) reduces to;

$$u = k_2 r^{1/2}$$

where

$$k_2 = 2.2\times10^3\left(\frac{\lambda_0}{\lambda}\right)^{1/2} \mathrm{cm}^{-1/2}\mathrm{sec}^{-1} \quad (10)$$

Where

λ → Air density

λ_0 → Reference density of air at 1013 hPa pressure level

More accurately the terminal fall speed of the particles is given by;

$$V_T = \left(\frac{4\lambda_h g}{3C_D\lambda_a}\right)^{1/2} D^{1/2} \quad (11)$$

Where

λ_h → Particle density

λ_a → Air density at different levels

g → Acceleration due to the gravity

The particle whose fall speed is matched by local updraft speed will remain suspended in air stream and would continue to grow by the process of accretion or condensation. The fall speed V_T of the spherical particle of diameter D is extremely important.

Thus, taking

$W(z) = V_T$

The upper limit of the size of the particle present in the mixed phase within 0 to (–) 40 degree Celsius can be computed. The droplet aloft adopts the updraft speed and hence the maximum particle size can be estimated in the mixed phase region. The updraft speed of interest is typically at the altitude significantly less than the LNB. The results of the present study show that the updraft in the range of the 10 – 20 m/s can provide the growth of particles size within the range of 1 mm – 10 mm in diameter. It is apparent for the ordinary thunderstorms occurring in the mixed phase. For the updraft speed of 20 - 50 m/s, the particles could be beyond 20mm in diameter and this can lead to the development of a severe thunderstorm provided that other conditions favour. However in case of the drops, the maximum size could barely exceed the typical range of 1 mm – 5 mm in radius. The droplets can further grow in the absence of the shear or the random process of collision, but these situations are ideal in the severe thunderstorms. Beyond this range of diameter, the droplets actually breaks up as the force of the gravitation increases so much that the surface tension forces cannot hold the drops together.

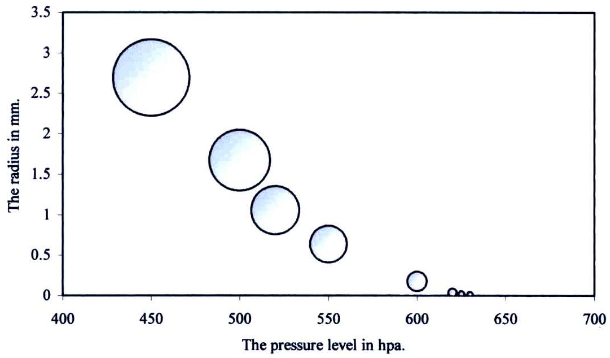

Fig. 1. Schematics showing the variation of the radius of cloud droplets with pressure levels on 11th April 1997 (0000 UTC) over Kolkata

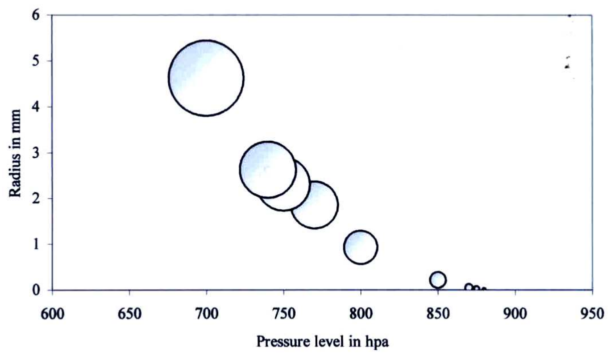

Fig. 2. Schematics showing the variation of the radius of cloud droplets with pressure levels on 11th April 1997 (1200 UTC) over Kolkata

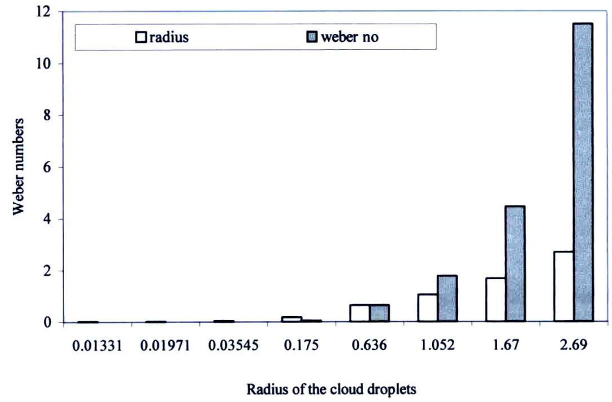

Fig. 3. Schematic showing the variation of the Weber Number with droplet radius at 0000 UTC on 11th April 1997 over Kolkata

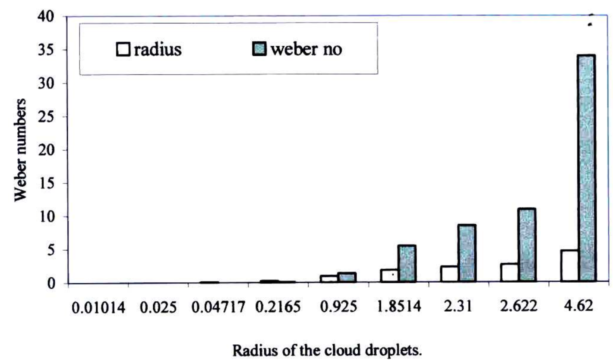

Fig. 4. Schematic showing the variation of the Weber Number and cloud droplet radius on 11th April 1997 (1200 UTC) over Kolkata

2.4. *Computation of drop breakdown with significance of Weber number*

In this section those conditions will be considered under which the isolated falling drops become dynamically unstable and breakup. Many scientists carried out experiments with drops falling through a long column of air at rest and with drops suspended in the low turbulence (Pruppacher and Klett, 1980). The wind tunnels have demonstrated that the drops can grow as large as the radius of about 4.5 mm before break up. The present study, using the concept of Weber number, shows that such large drops can really exist in the severe thundercloud. Since the drop breakup depends very much on the surface tension, the Weber number can be considered for the deterministic specification of the required radius range for the drop breakdown. It is the measurement of the relative strength of the Bernoulli pressure and stress due to the surface tension, which is mathematically expressed as

$$N_{\mathrm{WE,MAX}} = \left(\lambda_a \mathrm{d}_{\mathrm{MAX}} U_{\infty}\right)/\sigma \tag{12}$$

Where

λ_a → Density of the air

σ → Surface tension = 72.8 ergs /cm^{-2}

U_{∞} → the updraft speed

It is therefore apparent that if $N_{\mathrm{WE}} >> 1$ then the surface tension stress, which helps to maintain a spherical shape, is practically negligible in comparison to the pressure, so that the latter can distort the drops. As N_{WE} tends to 10, the droplets break up.

The importance of the droplets for which the Weber's no is greater than 1 lies in the fact that such drops

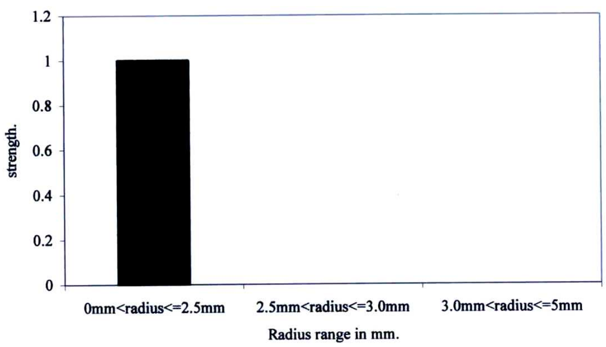

Fig. 5. Schematic showing the range of the particles in which they are resistant towards splitting for the thunderstorm over Kolkata on April 1997

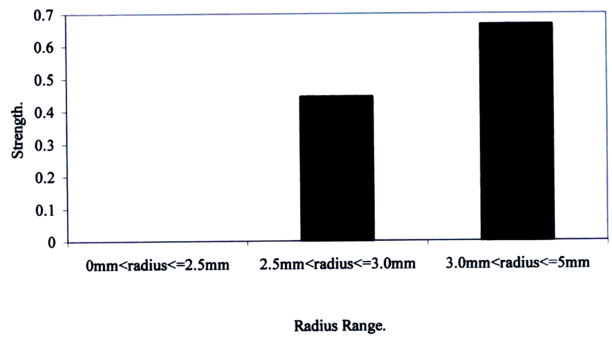

Fig. 6. Schematic showing the variation of strength of instability and splitting at different radius range for the thunderstorm over Kolkata

can bear the induced charges under the effect of the electric field and can deform under the action of increasing electric fields. Such drops are therefore important for the purpose of preliminary breakdown. Thus the Weber number can be considered as the most important parameter in relation to the cloud microphysics.

2.5. *Application of soft computing in quantification of the range of droplet radius*

The derived data archive including the Weber number and the radius of the cloud droplets at various pressure levels have been analyzed for the six severe thunderstorm days reported by Regional Meteorological Office, Kolkata, using the soft computing technique in the form of Rough Set Theory to specify the range of radius to which the droplets are resistant to splitting and the range in which splitting is prone.

Soft computing techniques are of frequent use now a day in the field of applied sciences where the assignment is pattern recognition or forecasting. This computational procedure is highly applicable in the fields of meteorology where most of the parameters/phenomena are highly nonlinear and chaotic in nature (Chaudhuri and Chattopadhyay, 2001, 2002, 2003, 2004, 2005). Plenty of literature is available where application of soft computing in the field of atmospheric sciences is applied.

Rough Set Theory belongs to that category of soft computing technique where some crisp ideas are to be built up on the basis of imprecise data set (Chaudhuri and Chattopadhyay, 2003). The crisp theory is only possible for the idea of "belongs to or does not belongs to". The concept cannot bring out crisp results where the data structure itself has a significant degree of indiscernability. In Rough Theoretic approach to a data set, a decision algorithm is framed based on "cause & effect" thought. A sequence of causes ($C_1, C_2 \ldots C_n$) is constructed to take a sequences of decisions ($d_1, d_2 \ldots d_n$). Corresponding to each cause or decision, a set can be built up. The strength of each decision is computed using the relation;

$$\text{Strength} = \frac{|C_i \cap d_i|}{|C_i|} \qquad (13)$$

In the present problem, two decision algorithms are framed;

If $0 < N \leq 0$ then $0 < \text{Radius} \leq 2.5$mm

If $N > 10$ then 2.5 mm < Radius < 5mm

3. Results & discussions

Figs. 1 & 2 show the variation of the maximum cloud droplet radius at various levels at 0000 and 1200 UTC respectively on 11th of April 1997, a reported severe thunderstorm day accompanied with hail. Fig. 1 depicts that the cloud droplets at the 450 hPa pressure level is only 2.69 mm in radius and the status of the large drops of radius 1.052 mm is at about 520 hPa pressure level. Fig. 2 shows that the size of the cloud droplet is 4.62 mm in radius at 700 hPa and the droplets achieves the status of the large drops of radius 1.8514 mm at the pressure level of 770 hPa during 1200 UTC which is much lower compared to 0000 UTC clouds. It can thus be clearly stated that that the large droplets of 1200 UTC clouds can reach to the ground more easily compared to that of the 0000 UTC cloud in which the large drops are formed at much higher altitudes. It can therefore be stated that at 0000 UTC on 11th April the cloud cells were in the cumulus stage of development whereas at 1200 UTC the cloud cells turned to matured stage when the droplet radius are much larger from much lower heights within the cloud.

Fig. 3 shows the variation of Weber number with the radius of the cloud droplets at 0000 UTC on 11th April 1997. The figure depicts that the Weber number for the droplets of radius less than 1 mm are lower than 1. These particles therefore have high surface tension, which facilitates to retain their spherical shape. The value of the Weber number obtained to be 1.768 for the drop radius of 1 .05 mm and is 11.5 for the drop radius of 2.69 mm. Thus the droplets of radius ranging between 1 mm and nearly 2.5 mm have the Weber number within the range of 1 and 10. Within this range therefore the droplets get distorted. The droplets exceeding the radius of 2.5 mm begin to break. The cloud droplets reaches this value at a much higher altitude of 450 hPa and thus the splitting processes in this cloud cell initiates from much higher altitude. During 1200 UTC (Fig. 4) on the other hand, radius of the droplets corresponding to Weber number between 1 to 10 is nearly 1 to 10 mm and the drop radius is 4.62 mm with N = 34. These droplets are therefore prone for splitting at the height of 3000 m or 700 hPa pressure level. This being at a matured state of development all the microphysical processes is much active.

Fig. 5 shows that the droplets between the radii of 0 mm to 2.5 mm have the Weber number less than 10. These droplets are therefore resistant to splitting but they can undergo the distortion in their shapes.

Fig. 6 shows that the drop radius typically between 2.5 mm to 5 mm are more prone to splitting but the drops within the range of 3 mm to 5 mm have maximum tendency towards breakup due to the large drop instability.

4. Conclusion

The study leads to conclude that CAPE is instrumental in viewing the microphysical processes during severe thunderstorms. The droplets of radius within the range of 1 mm to nearly 2.5 mm have the Weber number ranging between 1 and 10. Thus the droplets get distorted and as the droplets cross the radius of 2.5 mm they tend to break.

The drop radius typically between 2.5 mm to 5 mm is more prone to splitting whereas the drop radius within the range of 3 mm to 5 mm have maximum tendency towards breakup due to the large drop instability.

References

Chappell, C. F. and Smith, D. R., 1975, "Generation of the available buoyant energy by cloud glaciations", *PAGEOPHYS*, **113**, p825.

Chaudhuri, S. and Chattopadhyay, S., 2001, "Measure of CINE - A relevant parameter for forecasting pre-monsoon thunderstorm over GWB", *Mausam*, **52**, 4, 679-684.

Chaudhuri, S. and Chattopadhyay, S., 2002, "Multilayer perception model in pattern recognition of surface parameters during the pre-monsoon thunderstorm", *Mausam*, **53**, 4, 417-424.

Chaudhuri, S. and Chattopadhyay, S., 2003, "Genesis of severe local storms - A genetic algorithm approach", *Science and culture*, **69**, 331-335.

Chaudhuri, S. and Chattopadhyay, S., 2004, "Consequences of pre-monsoon thunderstorm -A fuzzy logic approach", *Mausam*, **55**, 1, 119-122.

Chaudhuri, S. and Chattopadhyay, S., 2005, "Neuro-computing based short range prediction of some meteorological parameters during the pre-monsoon season", Soft Computing - A Fusion of Foundations, Methodologies and Applications: Springer-Verlag ISSN: 1432-7643 (Paper) 1433-7479 (Online) DOI: 10.1007/s00500-004-0414-3, 1-6.

Chaudhuri, S. and Chattopadhyay, S., 2005, "Prediction of Severe Thunderstorms with minimal a-priori information", *Adv Complex System (Accepted)*.

Houze, R. A., 1989, "Observed structure of mesoscale convective system and implications for large scale heating", *Quart. J. Roy. Met. Soc*., **115**, p425.

Pruppacher, H. R. and Klett, J. D., 1980, "Microphysics of clouds and precipitation", D. Reidel Publishing Company, Dordrecht Holland.

Williams Earle, R., 1995, "Meteorological aspects of thunderstorm", Handbook of Atmospheric electrodynamics, 27-47.