Role of collision-coalescence mechanisms in the occurrence of cloudburst event

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Abstract

A cloudburst is an event with a precipitation rate higher than 100 mm hr^{-1} over a small geographical location of around 20-30 Km^2. It is unknown which processes control the occurrences of such a high rain rate, mainly due to the unavailability of the observations. For this purpose, the idealized simulation of the cloudburst event that occurred at 06:00 UTC on 10 June 2021 over Sauni Binsar, Uttarakhand, India, has been carried out. ERA5 reanalysis data initialized the idealized experiment. The height of the lifting condensation level (LCL), lifting deposition level (LDL), and lifting freezing levels (LFL) have been estimated. The simulations in the idealized cloud environment were carried out at 100 equidistance vertical levels between LCL and LDL. The collision and coalescence efficiencies, flow regimes, in-cloud turbulence, and droplet breakup dynamics have been simulated in this idealized cloud environment.

The synoptic analysis of the cloudburst indicated a continuous accumulation/stagnation (at 850 hPa) of moist air over Sauni Binsar due to the northward propagation of the southwest monsoon, which supersaturated the atmospheric column. The advection of warm air (dry) from the monsoon heat low at a higher (at 700 hPa) level caused potential instability over this region, as indicated by values of Richardson's number at the mid-upper troposphere. The orographic lifting and a gradual increase in the convergence over this region caused moist convection. Just a few hours before the cloudburst event (02-06 UTC 10 June 2021), the decrease in potential vorticity indicated the squashing of the moist columns and the reduction in the potential vorticity. The sudden squashing of the supersaturated atmospheric column might have caused enormous amounts of rainfall (Cloudburst) over the Sauni Binsar region.

The magnitudes of collision/coalescence efficiency play a vital role in producing a very high rainfall rate over a short time span around a localized area through the collision-coalescence process between the cloud droplets inside clouds. Therefore, the comparative performance of collision and coalescence efficiencies have been investigated to identify the appropriate formulation that determines higher collision/coalescence efficiencies during cloudburst events. From the appraisal of eight collision efficiencies, it is found that the collision efficiency based on Onishi et al. (2015), Beard and Grover (1974), Bohm (1999), and Jin et al. (2019) estimated high values of collision efficiencies during the cloudburst event. Meanwhile, the estimated collision efficiency based on Ahmad et al. (2020) is high for specific bins only. The formulations by Barnet (2011), Long (1974), and Lee and Baik (2017), however, estimated

very low values of collision efficiencies during the cloudburst event. The comparative analysis of the six coalescence efficiencies concludes that the estimated coalescence efficiency value based on Ochs et al. (1991) has shown higher magnitudes, of around 60-100% for all cloud droplet's diameter, during the cloudburst event. The estimated coalescence efficiencies based on Seifert et al. (2005) and Chen and Liu (2004) have shown a moderate value below 80% during the cloudburst time. In contrast, for Low and List (1982a) and Beard and Ochs (1984), the estimated coalescence efficiency is slightly lower, with a peak below 70%, during a cloudburst event, for all collector cloud droplet diameters and small cloud droplet diameters. However, the estimated coalescence efficiencies based on Brazier-Smith et al. (1973) have very low values, not exceeding 20%, during cloudburst events for all collector and small cloud droplet diameters.

The in-cloud turbulence and changes influence the collision-coalescence-breakup mechanism and affect the terminal velocities of cloud droplets (colliding and collector droplets). The transitions in different flow regions were classified based on the Knudsen number. The in-cloud terminal velocities and Reynold's number were estimated for 19 bins of collector droplets with diameters ranging from 50-7000 μm and nine bins of small droplets with diameters ranging from 1-500 μm. The study results concluded that the flow of cloud droplets is influenced by droplets' diameter, terminal velocity, and cloud turbulence. The simulated terminal velocity in the idealized experiment is as high as 52 m s^{-1}. The analysis of the Reynolds number shows that the rotational flow with periodic discharge of vorticity mainly characterizes the flow inside the cloud. The continuum of gas dynamics influences the flow of collector cloud droplets, while the rarefied gas dynamics determine small cloud droplets' flow. The flow associated with collector and small cloud droplets have different characteristics at different times, and other equations are required to describe their flow regimes. Hence, the multiphysics aspect must be considered in order to develop future microphysics parameterizations.

The cloud droplet breakup is an essential aspect that controls the maximum size of the cloud droplets. The magnitude of dynamical parameters viz. Weber number and collision kinetic energy (CKE) control the relative size of cloud droplets and different types of droplet breakup processes inside the clouds during the collision-coalescence mechanisms. Hence, it is essential to investigate the time altitudinal variation and relative magnitude of Weber number and collision kinetic energy (CKE) and their impacts on the collision-coalescence process. The collision between the collector cloud droplets of diameter 50-350 μm with small cloud droplets has produced fewer large-sized fragmented droplets with a Weber number of less than 350.

The collision between collector cloud droplets of diameter 350-2500 μm with small cloud droplets of small diameters has produced large to medium-sized fragments that also underwent multiple breakup processes for Weber numbers greater than 350 through bag and sheet breakup mechanisms as the size of small cloud droplets increased. The collision between the collector cloud droplets of diameter 2500-7000 μm and small cloud droplets has produced relatively small fragmented droplets through the sheet breakup mechanism. The fragmented droplets have undergone multiple breakups to form several small droplets during the collisions as the size of small droplets increases for Weber numbers less than 350. The estimated CKE value for collision between collector cloud droplets of diameter 350-7000 μm with collected droplets of small diameters indicates favorable conditions for undergoing a mechanism with a CKE value less than 200 times 10 to the less than 200×10^{-7} Joule. The collision between the collector cloud droplet diameter 2000-7000 μm with large and small cloud droplets is unfavorable for undergoing coalescence mechanism with higher CKE value greater than 200×10^{-7} Joule.

The higher values of collision and coalescence efficiency during the cloud burst event indicated that most of the cloud droplets underwent growth inside the cloud. Droplet breaking was confined to the collision of large collector droplets with small collected droplets, mainly in the droplet diameter of 350-7000 μm. This collision-coalescence-breakup mechanism might have produced raindrops of more than 500 μm. The *sudden squashing* of super-saturated with respect to liquid and solid water might have *significantly enhanced* the *cloud droplets concentration, facilitating* the further enhancement in the rate of the collision-coalescence mechanism. Further, the *deposition nucleation processes* (when water vapors might be directly deposited on the ice surface) and collision-coalescence process were initiated at the same height level as indicated by the *coinciding* of LCL and LDL heights during the cloudburst. They indicated supersaturation and availability of mixed-phase hydrometeors at the LCL heights. In addition, high turbulence and large terminal velocity might have produced a high rain rate and might be responsible for the cloudburst. Thus, the collision-coalescence-breakup mechanism was vital in heavy precipitation over Sauni Binsar. However, the role of the other cloud microphysical processes under idealized conditions needs to be investigated to know their relative contribution to the cloudburst event.