Visualization of Droplet Dynamics in Cloud Turbulence

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Abstract

The study of droplet dynamics is a crucial part of cloud physics and involves investigation of each and every droplet's properties. It is difficult to carry out such investigations using field observations. Small scale simulation is one method to study such phenomena, and visualization of these processes provides a deep and quick understanding. This work depicts data obtained from Direct Numerical Simulation (DNS) of entrainment and mixing processes at a cloud's edge, which affect the droplet dynamics due to evaporation and condensation. This simulation contains coupled Eulerian and Lagrangian frames. Animations are created for both Eulerian grid data and Lagrangian droplet movement. Scientific visualization provides a way to examine these turbulent properties in a particular part of a cloud and learn about droplet evolution and mixing phenomena in such highly turbulent areas.

1. Introduction

Clouds play an important role in the earth-atmosphere system by influencing the Earth's radiation budget and water cycle. The effects in the system occur through natural processes like reflecting solar radiation and regulating the atmospheric hydrological cycle. These processes are directly related to cloud micro-physical properties involving turbulent entrainment and mixing of cloudy and clear air, which affects droplet size distribution (DSD). The turbulent entrainment and mixing of dry air with cloudy air determines the lifetime of the cloud by changing the properties of DSD. The droplet dynamics are responsible for these changes.

The mixing process continues until the mixture becomes saturated. During this mixing, either all of the droplets can evaporate by the same amount, or a subset of droplets evaporates completely while the other remains unchanged. The first type of mixing is known as homogeneous mixing and the latter, in-homogeneous [1]. This mixing process is quite complex and it is difficult to study it during field observations. Numerical simulations are alternate approaches to study this process. Since this mixing occurs at small spatial scale, very high-resolution computer simulations are required. In this work we have adopted Direct Numerical Simulation (DNS) to simulate the turbulent flow and droplet movement therein [2, 3, 4].

Thorough investigation of the droplet dynamics in such turbulent flow is needed to understand the type of mixing and broadening of DSD. The dynamics include the size of and movement of droplets. In general, DSD is generated using a probability density function (PDF) from simulated/observed data. However, it remains unclear in which part of the cloud inhomogeneous mixing and rapid droplet size reduction occur, and in which part droplets are staying in a relaxation (equilibrium) state.

Such areas in the cloud are responsible for radiative properties and the life time of the cloud. Furthermore, these cloud properties change with time, temperature, and other meteorological properties during the entire life span and in every part of the cloud.

3D visualization is the right tool to study such phenomena at different parts of clouds. It can help to investigate the cloud properties more closely at different locations. In this visualization we can see the droplet movement and sizes at different parts of a cloud within a computational domain using data obtained from DNS. The detail of the computational domain data is provided in a subsequent section.

This paper is organized as follows. The next section provides a description of the numerical model used in the simulation, followed by details of the data set and I/O in section three. The visualization techniques are detailed in section four. Section five presents the conclusion of this study.

2. Numerical Model

The governing equations for turbulent flow as well as droplet growth and movement are taken from Kumar, et. al., 2014 [1]. The fluid flow equations for the turbulent fields, namely the velocity field u, the vapor mixing ratio field q_v, and the temperature field T, are as follows

$$\begin{aligned}
\nabla \cdot \mathbf{u} &= 0\,, && (1)\\
\partial_t \mathbf{u} + (\mathbf{u}\cdot\nabla)\mathbf{u} &= -\frac{1}{\rho_0}\nabla p + \nu\nabla^2\mathbf{u} + B\mathbf{e}_z + \mathbf{f}_{LS}\,, && (2)\\
\partial_t T + \mathbf{u}\cdot\nabla T &= \kappa\nabla^2 T + \frac{L}{c_p}C_d\,, && (3)\\
\partial_t q_v + \mathbf{u}\cdot\nabla q_v &= D\nabla^2 q_v - C_d\,. && (4)
\end{aligned}$$

The reference density ρ_0 is the dry air density. The buoyancy term in the momentum equation is defined as

$$B(\mathbf{x},t) = g\left[\frac{T-T_0}{T_0} + \tilde{\varepsilon}(q_v - q_{v0}) - q_l\right], \tag{5}$$

where $\tilde{\epsilon} = R_v/R_d - 1 \approx 0.608$. R_v is the vapor gas constant and R_d is the dry air gas constant. The additional term f_{LS} at the right hand side of equation (2) keeps the flow in a statistically stationary state during the mixing process, i.e., throughout the simulation. This term is used to model the driving of the entrainment process resulting from larger scales (LS) which go beyond the volume size considered here [2], [1].

There are three set of equations for droplet evolution

$$\frac{\mathrm{d}\mathbf{X}}{\mathrm{d}t} = \mathbf{V}(\mathbf{X}, t)\,, \tag{6}$$

$$\frac{\mathrm{d}\mathbf{V}}{\mathrm{d}t} = \frac{1}{\tau_p}[\mathbf{u}(\mathbf{X}, t) - \mathbf{V}(\mathbf{X}, t)] + \mathbf{g}\,, \tag{7}$$

$$r(\mathbf{X}, t)\frac{\mathrm{d}r(\mathbf{X}, t)}{\mathrm{d}t} = KS(\mathbf{X}, t)\,. \tag{8}$$

Here, X is the droplet position, V its velocity, and r the radius. The cloud water droplets are described as inertial point particles with a finite particle response time $\tau_p = 2\rho_l r^2/(9\rho_0 \nu)$ which can grow and shrink by diffusion of vapor to their surface. The vector g is the gravitational acceleration. The constant K in equation (7) is a function of temperature and pressure, and incorporates the self-limiting effects of latent heat exchange (see e.g. Rogers, et. al. [5]). This diffusional growth is controlled by the supersaturation, given by $S(\mathbf{X}, t) = q_v(\mathbf{X}, t)/q_{v,s}(T) - 1$.

The saturation vapor mixing ratio $q_{v,s}(T)$ has to be determined from the temperature via the Clausius-Clapeyron equation.

In DNS, equations are solved directly without any parameterization or assumptions. As is evident from the above set of mathematical equations, the model has two frames of reference, namely, a Eulerian frame and a Lagrangian frame. Accordingly, the numerical scheme consists of two parts: first, fluid flow equations solved on grid points in the computational domain, and second, droplet dynamics equations representing their motion inside a grid cell as well as their evolution due to condensation and evaporation. At each time step droplet positions change due to turbulent flow, and this movement also causes a change in their sizes because of condensation and evaporation. Both sets of equations are solved numerically, which requires development of parallel algorithms. The 3D physical domain (in X, Y, and Z directions) is divided into two dimensional processor topology as shown in Figure 1.

The implementation of such an algorithm requires a huge amount of computational resources to manage the large amount of data in both the Eulerian grid points, as well as in the Lagrangian particle tracking, as described in next section. One specific challenge is parallel Lagrangian particle tracking, which calls for inter-processor communication at every time step.

The simulation was carried out using 8096 cores on an IBM iDataPlex cluster equipped with Intel Sandy Bridge processors.

3. Data Set and I/O

The DNS data consist of a computational domain of 2.048 m per side with a grid size of 1 mm, amounting to 2048^3 grid cells.

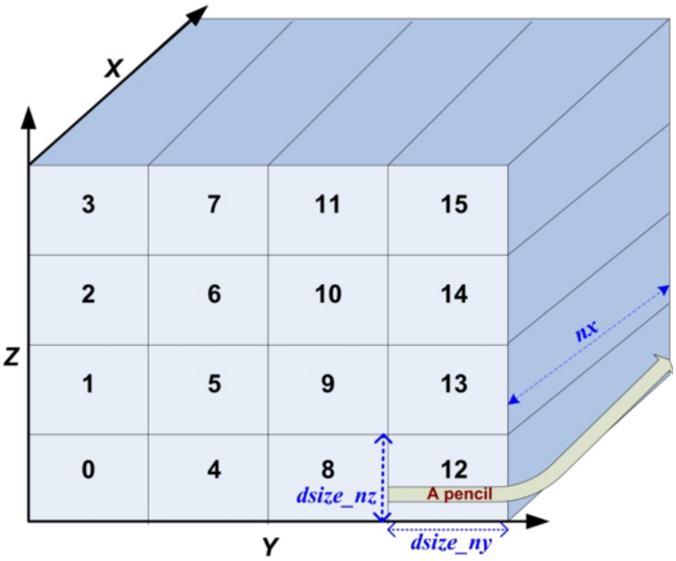

Figure 1: Illustration of 3D physical domain decomposed in 2D processor topology. Here, each processor gets data as a pencil having part of the data divided in 2 directions (say Y and Z) and keeps the whole amount of data in a particular direction (say X). 'nx'is the total number of particles in the X-direction, and dsize_nz and dsize_ny are the number of particles in the Z and Y directions at each processor after decomposition.

The number of droplets in the domain was calculated using a density of about 120 droplets per cm^3, giving a total count of approximately 434 million droplets. Furthermore, each droplet contains about 10 properties including identity number, position in three directions and radius. All of these values were written with double precision.

The droplet data were written in parallel using the SION Lib [6] parallel library. The raw data contains all droplet properties including position, velocities, size, temperature, vapor mixing ratio, global identity and processor identity for each particle. It should be noted that each processor contains a different number of droplets, and this information is provided in the metadata for the raw file. For the data analysis from raw data, one has to use the SION Lib, however this binary data can be converted into a format required by visualization software.

The Eulerian gridded data was written in parallel in netcdf format using the pnetcdf library [7]. Each file has the values of five variables, namely, position in X, Y, Z directions, temperature and vapor mixing ratio at each grid point of 2048 x 2048 x 2048 grid cells. In this file format, each processor has an equal amount of data which is written to the file in parallel. The 'netcdf' format is a very common file format and is compatible with most visualization software.

4. Visualization Techniques

The unstructured droplet data, consisting of X, Y, and Z coordinate values and a radius scalar value for each droplet, were well suited for ParaView points rendering [8]. Due to the very large quantity of droplet data, a spacing of every five particles was chosen as a compromise between rendering time and the amount of particles necessary to visually represent the mixing.

Additionally, the renders were created with a high enough resolution to create final animations at 3840 x 2160 pixels. Even at such a high resolution, images with denser spacing, more data, and longer render times were not easily visually distinguishable from images made with five-particle spacing.

The data were colored by radius of droplets using a diverging color map, allowing viewing of the color span and difference between close scalar values [9]. Divergent color maps are optimal for showing positive and negative values centered around a point [9], however, in this situation this type of map was useful to highlight the contrast between smaller radii and larger radii in the full domain. It would otherwise be difficult to distinguish the difference in sizes due to the high density of the data. Rendering the particles based on size was also considered, however it was determined that the particle size was small enough compared to the overall domain that the size gradient would not be as clearly visible as it is when using two colors.

It is worth noting that various other visualization methods were considered but not yet utilized due to time constraints. These included tracing the path of a single particle or small group of particles and sending line tracers through the Eulerian vector field. These techniques and others will be explored in future studies. Additionally, the time spacing for this visualization was required to be quite sparse due to the large spatial dimension and resultant file sizes. Future efforts will focus on smaller domains and a much higher time resolution, which will greatly enhance the fluid flow of the animation.

OSPRay [10] ray tracing was enabled to help visualize the particle motion. The use of shadowing, such as that created by ray tracing, was needed to give the perception of depth in the expanding particles. This was especially critical for earlier time steps, where the particle radius is still relatively homogenous and the particles appear as a single block of solid blue. (Figure 2).

A subset of the droplets was selected on which to zoom the camera in for closer observation of the boundary between the larger (blue) droplets and the smaller (red) droplets. This boundary is significant to understand the effect of the mixing process on droplet size distribution. In particular, one can easily view the evaporation process indicating in-homogeneous mixing occurring at the cloud-clear air interface. Furthermore, zooming on this smaller domain also allowed for the viewing of all particles, without any spacing or reduction of particle count. (Figure 3).

The Eulerian data were visualized using a linear color map of grayish coloring, representing natural cloud coloration. The cloud slab is clearly visible on the white end of the spectrum. (Figure 4) ParaView volumetric rendering was utilized, as this rendering method allows the visualization of such dense data while still observing the linear gradient of colors. Volumetric rendering also provides a cloud like effect, helping the viewer connect to the subject matter.

As with the droplet data, these Eulerian data points were reduced by spacing every three grid points to speed computational time.

The title slide of the visualization was created using Blender software [11], namely with Blender's point density ability [12]. This feature allows the creation of a volumetric density domain, in which the density is determined by vertices in space. The X, Y, Z values of the vertices were determined by the Lagrangian droplet values.

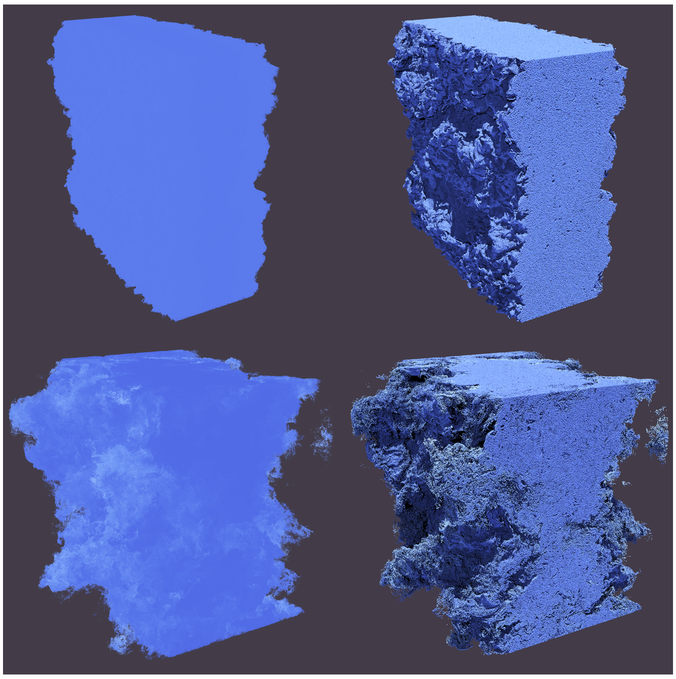

Figure 2: Droplet data of time step 2 (top row) and 12 (bottom row) visualized without OSPRay ray tracing (left column) and with ray tracing (right column).

5. Conclusion

The value of computer simulations to study complex systems, such as the cloud systems presented in this visualization, cannot be understated. Studying these systems in the field can be difficult, costly, or impossible, and therefore, computer simulations are necessary to be able to examine these systems in detail. This visualization of droplet evolution provided the opportunity to peek inside the cloud area and observe properties of individual droplets. These investigations are not possible with field observations or with traditional data analysis provided in literature. For example, the zoomed domain of this cloud has cast light on the issue of the turbulent attributes in this area which affect the cloud micro-physics properties. This study will be useful for readers or researchers working in the field of cloud turbulence.

Furthermore, visualization of the data generated by these systems is vital to understanding the nature of the data as well as to communicate results to scientific peers and the general public.

This presents a challenge, though, with the ever-increasing amount of data being generated. Due to time and logistical constraints, this particular version of the visualization was run on an individual PC using CPU processing only. Parallel computational methods, e.g., GPU and multi-core processing, and those described in Ahrens, et. al., [8] will be utilized in future studies. Distribution of computational efforts over multiple processors

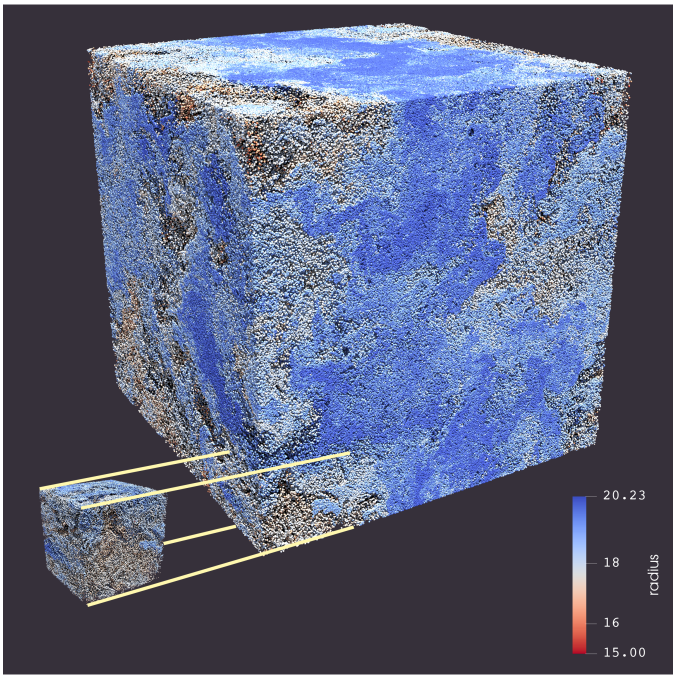

Figure 3: Approximate area used for zoomed visualization.

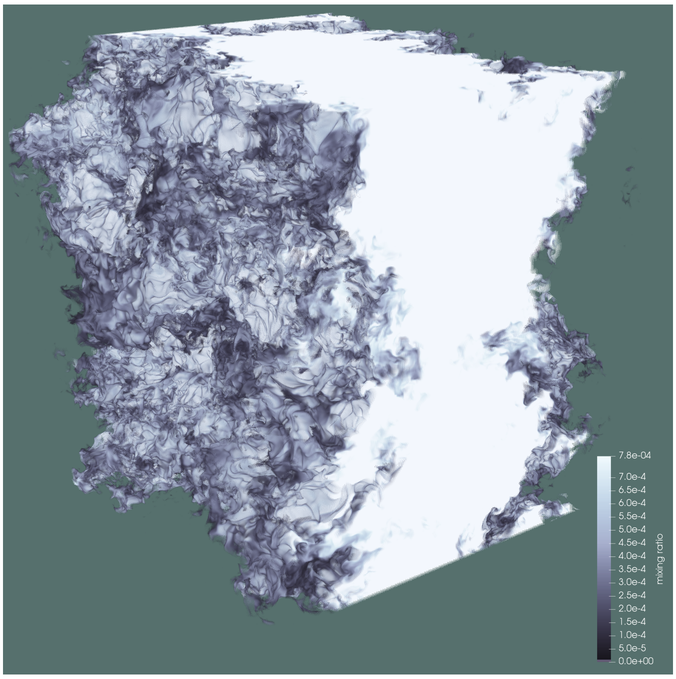

Figure 4: Mixing ratio variable of Eulerian data. The central cloud slab is clearly visible in white.

and memory would allow animating without requiring as much limiting or spacing of the data.

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