Multi-Scale Modeling of Turbulence and Microphysics in Clouds

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The physics of clouds involves an enormous range of spatial scales from global scale to droplet scale (10^7 m to 10^{-6} m). Even if we restrict ourselves to the scales of motion in a single small cumulus cloud, the range is still very large (10^3 m to 10^{-3} m). Current methods for simulating the physics of clouds typically focus on high-fidelity representations of either the large turbulent eddies or the droplet microphysics, through 3D large-eddy simulation (LES), 3D direct numerical simulation (DNS), or explicit droplet microphysics models.

Even with the advent of petascale computing systems, decreasing the grid size of LES from 10 m to 1 m requires a factor of 10^4 more CPU time. A typical 10-m-grid-size LES of a single cloud (320^3 gridpoints, 1 hour simulation) takes about 500 CPU hours on currently available processors. Using 5,000,000 CPU hours for a 1-m-grid-size LES will be feasible with a petascale computing system, but 1 meter is still 10^3 larger than the smallest scales of motion in atmospheric turbulence. These small scales of motion strongly interact with cloud droplets via inhomogenieties of the water vapor fields due to entrainment and mixing, and by turbulent accelerations of the droplets that increase collision rates among droplets. To resolve the smallest scales of motion in a turbulent cloud would require a factor of 10^{16} increase in CPU time over a 10-m-grid-size LES. It is simply not going to be feasible, even with petascale computing systems, to resolve such a huge range of motions in three dimensions.

However, using an alternative and extremely promising approach for explicit simulation (as opposed to parameterization) that reduces the dimensionality instead of the grid size, thus retaining the relevant physics, the increase in CPU time required to resolve the smallest scales of motion in a turbulent cloud would be $O(10^5)$, therefore requiring about 5×10^7 CPU hours on current processors. A similar approach is already being used in global models in which a 2D cloud-resolving model is embedded in each grid column of a 3D global model. In the analogous approach for LES, here called LES+ODT (one-dimensional turbulence), 3D aspects of the flow are captured by embedding three, mutually orthogonal, 1D ODT arrays within each LES grid cell., as shown in the diagram. In ODT the fields defined on the 1D domain evolve by two mechanisms: (1) molecular diffusion, and (2) a sequence of instantaneous transformations, denoted "eddy events," which represent turbulent stirring. Each eddy event may be interpreted as the model analog of an individual turbulent eddy. These eddy events occur over a large range of length scales, with frequencies that depend on event length scales and instantaneous flow states.