Abstract

Modeling of atmospheric clouds remain a challenge due to the range of length and time scales affecting their formation and evolution. We use computational and theoretical methods to analyze and model the phenomena of entrainment/detrainment and condensational growth of droplets in clouds. Towards this goal, we first perform LES (Large Eddy Simulation) simulations of jets and plumes with external bouyant forcing. However, numerical simulations of pure turbulent plumes for incompressible flow are known to be be unstable, primarily due to flow structures being advected into or out of the computational domain at the inflow/outflow/convective (IOC) boundary. To address this issue, we introduce sponge layers adjacent to the IOC boundaries, in which viscous damping of the flow field is carried out only in directions tangential to the boundary (Pant and Bhattacharya [2016]). This allows us to introduce a sharp jump in artificial viscosity inside the sponge layer, without introducing any spurious source terms in the momentum equation. This large viscosity damps the small scale flow structures at the IOC boundaries. Several numerical tests are carried out to show that results from Large Eddy Simulation (LES) of a pure thermal plume using the above viscous sponge layer scheme are independent of the size of the domain. This boundary condition is also used to simulate the multiple plume. The results of multiple plume are validated against the available literature.

We next use our LES solver to validate the approach by Kaminski et al. [2005] and van Reeuwijk and Craske [2015] for modeling entrainment rate coefficients. In this approach, the entrainment rate coefficient is constrained to be consistent with the energy equation. The consistency condition gives rise to an exact closure for the entrainment rate coefficient in terms of the radial heating, velocity and Reynolds stress profiles. LES of forced jet is conducted, and the data generated from the LES is used to validate the closure for entrainment rate coefficient. We build a 1-D model for a forced jet using the approach proposed by Kaminski et al. [2005] and van Reeuwijk and Craske [2015]. We use a mixing length model for the Reynolds stress, and we compare predictions

of the entrainment rate coefficent, velocity profile and evolution of jet width 1-D model with LES data of forced jet. We find that the 1-D model performs significantly better if the LES value of mixing length constant is used. The LES data shows that the flow can become significantly non-Gaussian outside the forced region; this causes significant differences in the result between the 1-D model and LES statistics. However, the 1-D model captures the bouyancy flux well, since it involves integral of velocity field over the region where the velocity field stays Gaussian.

For characterzing droplet growth in the presence of turbulent mixing, we devise an approach involving computationally efficient 2D simulations, which allows us to simulate large flow domains (e.g. 500 meters in length) with high (≈1 meter) resolution. We study the effect of grid resolution, Damkohler number, and initial size distribution of droplet, on the intermediate and final droplet size distribution. We find that the grid resolution (varied from approximate 1 meter to almost 10 meters) does not have a significant effect on the shape of the final droplet size spectra. The intermediate droplet size spectra does get affected by grid resolution, especially for smaller droplets. Overall, low grid resolution appears to smoothen the mixing interface, causing a larger number of droplets to undergo partial evaporation at intermediate times. We find that the main effect of Damkohler number (Da) is that, at higher values of Da, mixing gets delayed, and causes a larger number of droplets to evaporate completely; this is consistent with the current understanding of inhomogeneous mixing, which is supposed to take place at high Da.

References

E. Kaminski, S. Tait, and G. Carazzo. Turbulent entrainment in jets with arbitrary buoyancy. *Journal of Fluid Mechanics*, 526:361–376, 2005.

C. S. Pant and A. Bhattacharya. A viscous sponge layer formulation for robust large eddy simulation of thermal plumes. *Computers & Fluids*, 134:177–189, 2016.

M. van Reeuwijk and J. Craske. Energy-consistent entrainment relations for jets and plumes. *Journal of Fluid Mechanics*, 782:333–355, 2015.