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Gallery of Fluid Motion

Large-eddy simulation of cumulus clouds

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This paper is associated with a video winner of a 2021 American Physical Society's Division of Fluid Dynamics (DFD) Gallery of Fluid Motion Award for work presented at the DFD Gallery of Fluid Motion. The original video is available online at the Gallery of Fluid Motion, https://doi.org/10.1103/APS.DFD.2021.GFM.V0013.

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The representation of clouds in climate models is one of the largest sources of uncertainty in climate projections. In spite of recent advances in climate modeling, the Sixth Assessment Report of the Intergovernmental Panel on Climate Change states that "Clouds remain the largest contribution to the overall uncertainty in climate feedbacks" [1]. Atmospheric general circulation models (GCMs), the atmospheric component of climate models, have horizontal grid resolution of about 100 km. At such coarse resolutions, the effects of clouds are represented by parametrization schemes, which are specialized turbulence closures for these coarse fluid dynamical models. Parameterizations are developed using current cloud physics knowledge [2]. Observational data or results of higher resolution numerical models are used to tune and evaluate GCM parametrizations.

Large-eddy simulation (LES) is currently the best technique to provide reliable and well-characterized cloud modeling. Since direct numerical simulation (DNS) methods are not feasible for any atmospheric-scale flow, in the atmospheric sciences, LES is used similar to a DNS in the general fluid dynamics literature. LES modeling contributes to both fundamental studies of cloud physics and as a reference model in the development of parametrization schemes.

The GFM video corresponds to a large-eddy simulation of cumulus cloud convection over the ocean. The conditions observed during the Barbados Oceanographic and Meteorological Experiment (BOMEX) are simulated [3,4]. The LES model of [5] is used to simulate a volume of the atmosphere in a doubly periodic computational domain in the horizontal directions with size $5.12 \times 5.12 \times 3\ \mathrm{km}^3$ and 10-m uniform grid resolution. The flow is driven by latent and sensible heat surface fluxes, the large-scale horizontal pressure gradient, and forcings that account for the bulk effect of the atmospheric circulation on the boundary layer (see [4]). The LES model uses the buoyancy adjusted stretched vortex subgrid scale model [6] to represent the effects of unresolved turbulent motions.

Trade-wind shallow cumulus clouds are composed of liquid-water droplets, which strongly interact with solar radiation. Standard visualization techniques cannot realistically render clouds and clear sky, because they do not include the radiative transfer processes of absorption, emission, and scattering. The three-dimensional physics-based radiative transfer model of Villefranque *et al.* [7]

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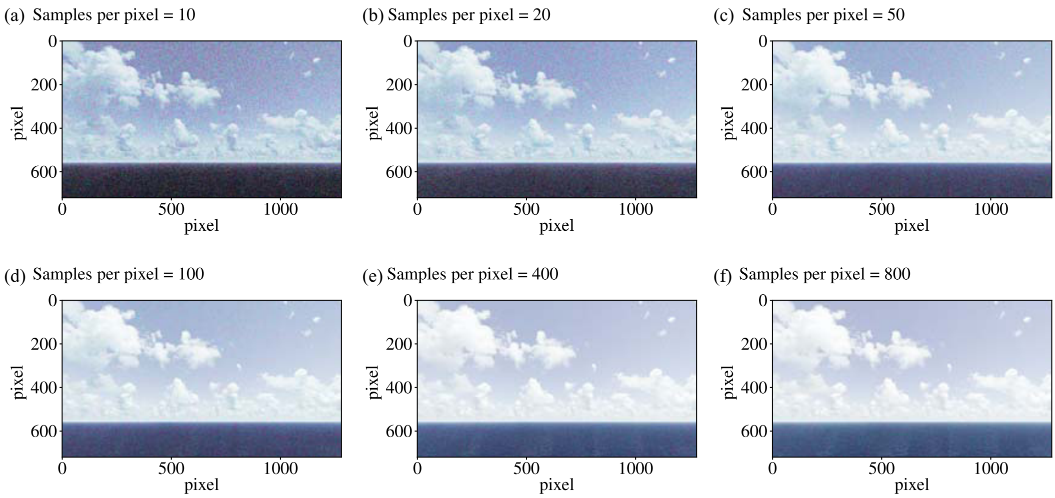

FIG. 1. Convergence of the three-dimensional radiative transfer rendering of the LES output. The LES corresponds to the trade-wind cumulus-topped atmospheric boundary layer observed during the BOMEX campaign. The same cloudy scene is rendered with an increasing number of samples per image pixel. As the number of samples increases, pixel-scale noise is reduced, resulting in smoother images.

is used to perform multispectral shortwave radiative transfer to realistically render the LES output. The radiative transfer uses a Monte Carlo method to track optical paths backward, from the observer position towards the atmosphere. To construct a simulated daylight image, three independent simulations are carried out to estimate the radiance incident at the camera. The three spectral components of the radiance field are converted into a standard red green blue (sRGB) image for visualization (see Figs. 1 and 2). In the radiative transfer calculation, a cloud droplet size distribution is assumed, droplets are homogeneous and polarization is ignored; see [7] for details.

Figure 1 shows the convergence of the radiative transfer calculation to "smoother" images with better color representation as the number of paths (or samples) per image pixel increases. For a sufficiently smooth image about 2000 samples per pixel are used. To render a single image, about 2

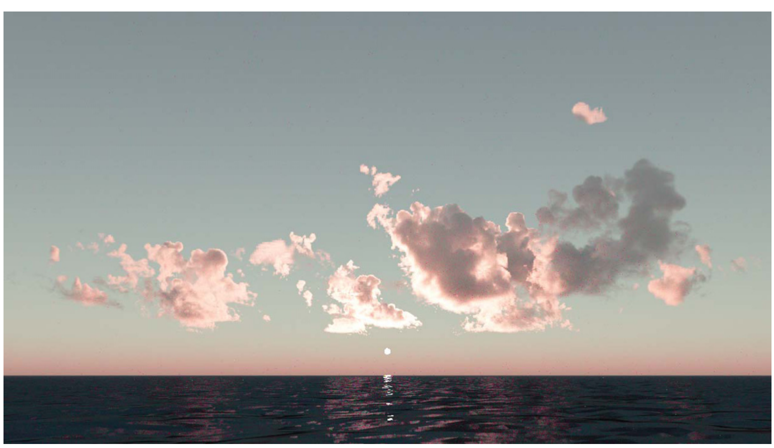

FIG. 2. A simulated sunset shows the realism and fidelity of the multispectral radiative transfer and simulated cumulus clouds. Specular reflection is visible on the ocean surface. The original video is available online at https://doi.org/10.1103/APS.DFD.2021.GFM.V0013.

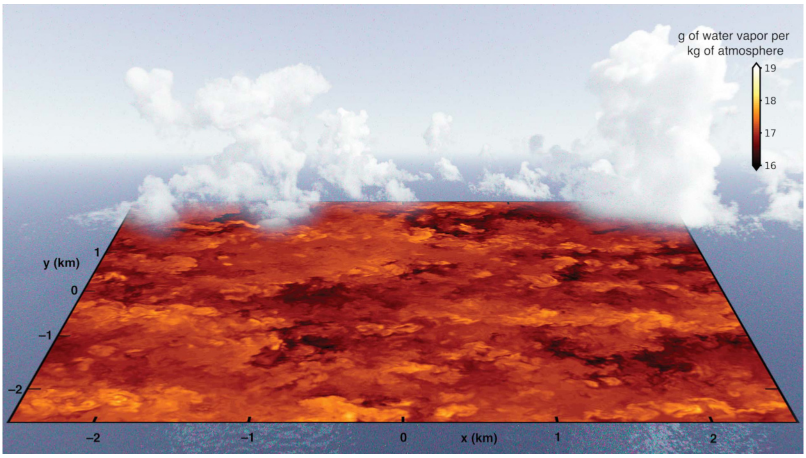

FIG. 3. Cloud field and specific humidity on a vertical plane at 200-m height. The original video is available online at https://doi.org/10.1103/APS.DFD.2021.GFM.V0013.

hours of wall-clock time are required using 36 CPU cores. The radiative transfer model facilitates different sun positions and viewpoint parameters. Figure 2 shows a simulated sunset demonstrating the realism and fidelity of the multispectral radiative transfer and LES cloud field. Figure 3 combines a visualization of atmospheric turbulence in the clear air with the cloud field. Specific humidity is plotted on a horizontal plane at 200 m, about half-height of the cloud-base height. Below the cloud base, the flow is continuously turbulent and is primarily influenced by buoyant convection and near-surface shear. Above the cloud base, turbulence is confined within the saturated updrafts that form the clouds.

The present images and GFM video demonstrate the fidelity of modern computational methods for the simulation of clouds and atmospheric turbulence. These simulations help address important questions in environmental fluid dynamics and atmospheric science, and contribute to improvements in weather forecasts and climate projections.

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