A three-dimensional atmospheric retrieval framework using an ensemble Kalman filter and three-dimensional radiative transfer

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As dynamical atmospheric models employ higher and higher resolution, there is an increasing need for equally high-resolution atmospheric retrievals to constrain the modeled physics. In the past decade or so, a new branch of retrieval algorithms has been developed to derive volumetric properties of the atmosphere using passive, multi-angle, and often polarimetric imagery, frequently referred to as atmospheric tomography [1, 2, 3, 4]. This technique can provide physics-based profiles of the three-dimensional (3D) atmosphere using 3D radiative transfer (RT) modeling, but they have computational and physical limitations. First, passive remote sensing is less sensitive to the atmospheric quantities when the optical thickness is large [1], limiting its capability to thin clouds. Application to deeper clouds would require additional information that supplements the physics-based retrieval, such as a-priori knowledge of typical cloud structures and collocated active remote sensing data. Second, these algorithms have often depended on a deterministic RT solver, the spherical harmonics discrete ordinate method (SHDOM [5]), to effectively construct the Jacobian and solve the inversion problem. While SHDOM has been extensively used in the remote sensing domain, the radiation community has seen a substantial computational improvement in another commonly used type of RT solvers, Monte Carlo (MC)-based RT models, further accelerated by parallelized graphical processing units (GPUs). MC-based RT solvers have built-in scalability of computational costs, which can improve the computational efficiency when low accuracy is tolerable, but this comes at the expense of added MC noise that impedes the derivation of the Jacobian.

To address these limitations, we explored a Bayesian framework for a multi-angle retrieval of clouds based on an Ensemble Kalman Filter (EnKF) [6, 7] and a MC-based 3D RT solver. We used large eddy simulation (LES) output to generate cloud fields as the ground truth, along with a corresponding set of synthetic multi-angle radiance imagery as input to the retrieval framework. Using a MC-based 3D RT model [8, 9] as the forward observation operator, we iteratively applied the EnKF to update the cloud field while minimizing the difference between the observed and predicted radiance without depending on the Jacobian. A priori knowledge of the spatial correlation of the cloud field was given from a large collection of LES output and was systematically ingested to compensate the lack of physical constraints (information content) in optically deep clouds. A preliminary test was done with LES-simulated oceanic shallow cumulus clouds [10] with spatial grid spacing coarsened to 2 km horizontally and 1 km vertically. The 3D could extinction coefficients were retrieved based on scalar radiance images from three viewing angles with a correlation coefficient of 0.7 within 12 iterations. Further developments are ongoing to apply a machine-learning algorithm in conjunction with the EnKF to effectively bridge between the physics-based approach and a priori information of clouds. Extension to polarized and multi-spectral radiative transfer is planned for extracting greater information content while speeding up the convergence particularly for higher resolution atmospheres.

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Preferred mode of presentation: Oral/Poster