A framework based on 2-D Taylor expansion for quantifying the impacts of sub-pixel reflectance variance and covariance on cloud optical thickness and effective radius retrievals based on the bi-spectral method

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The bi-spectral method retrieves cloud optical thickness $\tau$ and cloud droplet effective radius $r_e$ simultaneously from a pair of cloud reflectance observations, one in a visible or near infrared (VIS/NIR) band and the other in a shortwave-infrared (SWIR) band. A cloudy pixel is usually assumed to be horizontally homogeneous in the retrieval. Ignoring sub-pixel variations of cloud reflectances can lead to a significant bias in the retrieved $\tau$ and $r_e$. In the literature, the retrievals of $\tau$ and $r_e$ are often assumed to be independent and considered separately when investigating the impact of sub-pixel cloud reflectance variations on the bi-spectral method. As a result, the impact on $\tau$ is contributed only by the sub-pixel variation of VIS/NIR band reflectance and the impact on $r_e$ only by the sub-pixel variation of SWIR band reflectance.

In our new framework, we use the Taylor expansion of a two-variable function to understand and quantify the impacts of sub-pixel variances of VIS/NIR and SWIR cloud reflectances and their covariance on the $\tau$ and $r_e$ retrievals. This framework takes into account the fact that the retrievals are determined by both VIS/NIR and SWIR band observations in a mutually dependent way. In comparison with previous studies, it provides a more comprehensive understanding of how sub-pixel cloud reflectance variations impact the $\tau$ and $r_e$ retrievals based on the bi-spectral method. In particular, our framework provides a mathematical explanation of how the sub-pixel variation in VIS/NIR band influences the $r_e$ retrieval and why it can sometimes outweigh the influence of variations in the SWIR band and dominate the error in $r_e$ retrievals, leading to a potential contribution of positive bias to the $r_e$ retrieval. We test our framework using synthetic cloud fields from a large-eddy simulation and real observations from MODIS. The predicted results based on our framework agree very well with the numerical simulations. Our framework can be used to estimate the retrieval uncertainty from sub-pixel reflectance variations in operational satellite cloud products and to help understand the differences in $\tau$ and $r_e$ retrievals between two instruments.

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