A FAST HYBRID (3D/1D) MODEL FOR THERMAL RADIATIVE TRANSFER IN CIRRUS VIA SUCCESSIVE ORDERS OF SCATTERING

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Cirrus clouds are relevant components of the Earth's climate and radiation budget, but their role is still poorly understood. Many satellites are currently dedicated to cloud observation to retrieve their properties. Concerning cirrus clouds, Thermal InfraRed (TIR) retrieval techniques have demonstrated better accuracy than Visible/Near InfraRed (VNIR) and ShortWave-InfraRed (SWIR) reflectance channels techniques as long as the cirrus is optically thin with small ice crystals. However, current global operational algorithms assume that cloudy pixels are horizontally homogeneous (Plane Parallel and Homogeneous Approximation (PPHA)) and independent (Independent Pixel Approximation (IPA)). The impact of these approximations on ice cloud retrievals needs to be understood and, as far as possible, corrected. To better understand the effects of cloud heterogeneity on TOA thermal radiative quantities and potentially correct cloud parameter retrievals, 3D RT simulations are essential. They allow us to model the impact of cloud heterogeneity on cloud scattering for given microphysical/optical properties, conditional that these properties are realistic. However, full 3D RT calculations are generally very time consuming, particularly in Monte Carlo simulations.

The aim of this paper is to better understand the contribution of the different orders of scattering in the TIR atmospheric window, as has already been done in the solar spectrum. We focus our attention on the contributions of successive orders of scattering inside a heterogeneous cirrus cloud, with different scattering properties, for two of the three channels of the Imaging Infrared Radiometer on CALIPSO at 8.65 μm and 12.05 μm. Realistic 3-D cirri are modeled with the 3DCLOUD code, and top-of-atmosphere radiances are simulated by the 3-D Monte Carlo radiative transfer (RT) algorithm 3DMCPOL. Differences between 3D and 1D RT are discussed in terms of contribution of the successive orders of cloud scattering to the total radiance observed at TOA. We present a hybrid model (FATTIRE-C), based on exact 3D direct emission and 1D first scattering order in each homogenized column, followed by an empirical adjustment linearly dependent on the optical thickness to radically accelerate the 3D RT computations. We anticipate that a future deterministic implementation of the hybrid model will be fast enough to process multiangle thermal imagery in a practical tomographic reconstruction of 3-D cirrus fields.

Keywords: 3D thermal infrared radiative transfer, Monte Carlo, Cirrus

Spatial-scale Characteristics of Three-dimensional Cloud-resolving Radiation Budget by Monte Carlo Radiative Transfer Simulations

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Clouds have greenhouse effects that prevent cooling of ground surface and lower atmosphere by absorbing terrestrial infrared radiation, along with cooling effects by blocking the solar radiation. Those effects play an important role in determining the Earth's radiative energy budget which varies regionally and seasonally. Especially, in cloud-resolving scale, complex geometry and inhomogeneity of clouds affect significantly on three dimensional radiative energy budget of the solar and terrestrial radiation. Modeling of three-dimensional radiative processes and its spatial-scale characteristics is key issues for reliable simulations of cloud-resolving system.
In this study, three-dimensional atmospheric radiative transfer model has been developed for the purpose of evaluating the cloud-resolving radiation budget. Monte Carlo method has been employed as a basic scheme because the method is easily applicable to complex three-dimensional system rather than explicit analytical radiative transfer scheme. Multiple-scattering, absorption, and emission effects are taken into account to the radiative transfer process. The gas absorption data optimized with correlated-k distribution method are implemented in order for efficient broadband calculation. In addition, the dependent sampling method enables simultaneous calculations at multi-wavelength, which is suitable to sub-band integrations of the correlated-k distribution data.
The Monte Carlo radiative transfer model was applied to cloud scenes calculated by large eddy simulation model, and cloud-resolving radiative energy budgets were estimated for several different spatial-scales. Performance of the Monte Carlo radiative transfer model and the spatial-scale characteristics of three dimensional radiation effects will be discussed from the point of view of cloud-resolving radiation budget.

Assessments of Cloud Heterogeneity Effects on the POLDER3/PARASOL retrieved cloud parameters

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As recognized in the last IPCC report, clouds are of major importance in the climate budget and in its evolution. Their global and accurate observations are therefore essential. Since 2005 and during 9 years, POLDER3/PARASOL has measured total and polarized multi-angular reflectances of the atmosphere at three wavelengths. In a near future, the Multi-viewing, Multi-channel, Multi-polarisation Imager (3MI) will achieve the same kind of measurements with an extension to the shortwave infrared wavelengths.
These measurements allows to retrieve, among others, cloud optical thickness, cloud albedo, effective radius and variance of the size distribution and aerosol above cloud optical thickness. In the operational algorithm, clouds are still assumed, at the observation scale, flat, homogeneous and horizontally infinite. The consequence of this assumption needs to be evaluated.
Using three-dimensional (3D) synthetic cloud and 3D radiative transfer, we simulate realistic POLDER measurements. For bumpy and fractional clouds, we show that both total and polarized radiances are affected by the cloud heterogeneities. For example, the well-known illumination effects for titled solar incidence, lead to larger polarized radiances at small scale (50m). Consequently, the angular signature at POLDER scale (6x7km) used to retrieve some cloud parameters is modified by these illumination but also shadowing effects, that has to be added to the well-known plane-parallel bias due to the subpixel variability.
To assess cloud heterogeneity effects on operational product, we applied the POLDER operational algorithm on the simulated reflectances. The retrieval of cloud optical thickness is greatly affected by cloud heterogeneities. For solar incidence of 60°, the cloud optical thickness can be underestimated up to -70% in backward viewing direction and overestimated up to +40% in the forward direction. Concerning the cloud albedo, the errors are weaker, between -5% for low solar incidence angles and up to about 8% for large incidence angles. The cloud size distribution parameters retrieval that used multi-angular polarized reflectances, is almost not affected by the cloud heterogeneity. That proved to be a great advantage of polarization measurements. The cloud top pressure determining from molecular scattering in the forward direction can be biased up to 120hPa. Concerning the aerosol optical thickness above cloud the results show different pictures depending on the available angular information. When the scattering angle of the available directions range is between 60° and 180°, the retrieved AOT is almost not affected by the cloud heterogeneity. However, with only scattering angles above 120°, the algorithm retrieved significant amount of fictive aerosol.

Keywords: cloud, heterogeneity, Remote Sensing

CIRRUS HORIZONTAL HETEROGENEITY EFFECTS ON CLOUD OPTICAL PROPERTIES RETRIEVED FROM MODIS VNIR TO TIR CHANNELS

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Cirrus are an important part of the Earth radiation budget but an assessment of their role yet remains highly uncertain. Cirrus optical properties such as Cloud Optical Thickness (COT) and ice crystal effective particle size (Re) are often retrieved with a combination of Visible/Near InfraRed (VNIR) and ShortWave-InfraRed (SWIR) reflectance channels. Alternatively, Thermal InfraRed (TIR) techniques, such as the Split Window Technique (SWT), have demonstrated better sensitivity to thin cirrus. However, current satellite operational products for both retrieval methods assume that cloudy pixels are horizontally homogeneous (Plane Parallel and Homogeneous Approximation (PPHA)) and independent (Independent Pixel Approximation (IPA)). The impact of these approximations on cirrus retrievals needs to be understood and, as far as possible, corrected. Horizontal heterogeneity effects can be more easily estimated and corrected in the TIR range because they are mainly dominated by the PPA bias, which primarily depends on the COT subpixel heterogeneity. For solar reflectance channels, in addition to the PPHA bias, the IPA can lead to significant retrieval errors if there is large photon transport between cloudy columns in addition to brightening and shadowing effects that are more difficult to quantify.

The effects of cirrus horizontal heterogeneity are here studied on COT and Re retrievals obtained using simulated MODIS reflectances at 0.86 and 2.11 μm and radiances at 8.5, 11.0 and 12.0 μm, for spatial resolutions ranging from 50 m to 10 km. For each spatial resolution, simulated TOA reflectances and radiances are combined for cloud optical property retrievals with a research-level optimal estimation retrieval method (OEM). The impact of horizontal heterogeneity on the retrieved products is assessed for different solar geometries and various combinations of the five channels. Synthetic cirrus cloud fields used as input to the OEM are generated using a cirrus 3D cloud generator (3DCloud) and a 3D radiative transfer code (3DMCPOL).

Keywords: clouds, 3D effects, retrievals, satellite

Cloud inhomogeneity effect and its impact on cloud retrieval using passive satellite instruments

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Cloud optical and microphysical properties, together with cloud-top height, determine cloud radiative effects and impact Earth energy budget. While nature clouds are horizontally and vertically inhomogeneous, most of current retrieval algorithms consider cloud as a homogeneous layer in their forward models. In this study, cloud inhomogeneity effects are investigated in two different ways: (1) cloud sub-pixel inhomogeneity (horizontal inhomogeneous) and (2) vertical inhomogeneity (e.g., cloud microphysical property varies with height). We will show the impact from cloud inhomogeneity effects on current retrieval algorithms relying on observations of passive satellite instruments (e.g., infrared (IR) and/or solar reflectance observations). We also developed retrieval correction method to reduce biases due to cloud inhomogeneity effects.

Keywords: Cloud retrieval, Cloud inhomogeneity

Large Eddy Simulation and 3D Radiative Transfer Modeling in Support of Multi-Angle Remote Sensing of Clouds and Aerosols, With or Without Imaging

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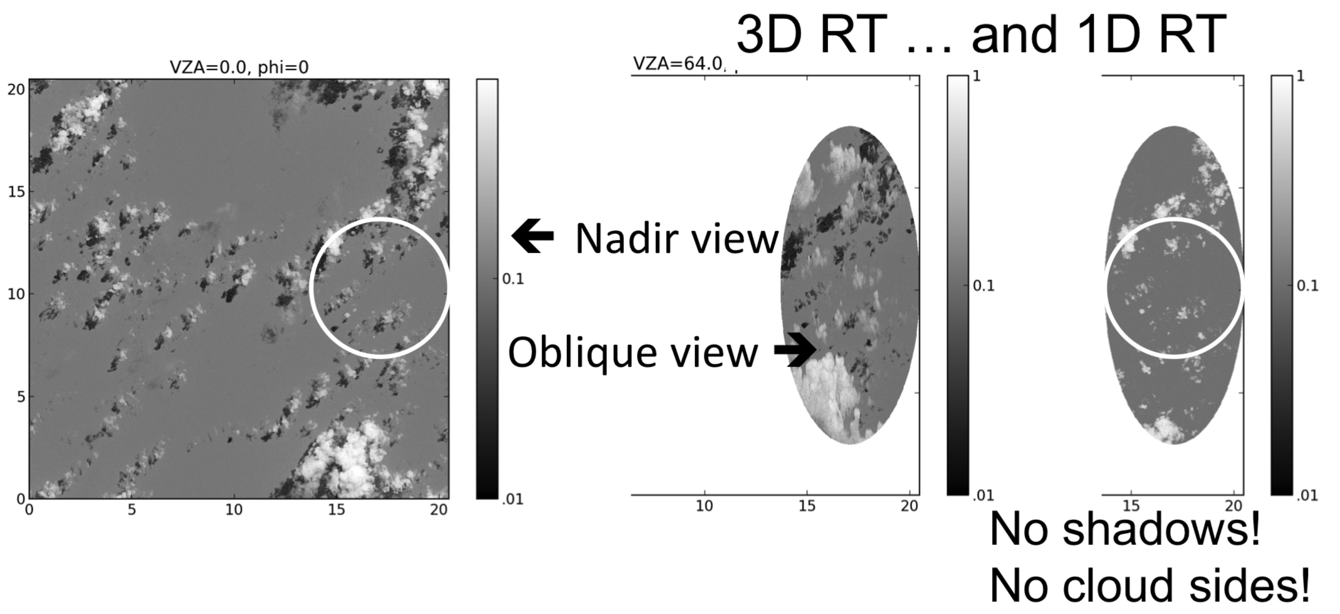
Although real clouds and aerosols vary in all three spatial dimensions, operational remote sensing of their inherent physical properties is invariably predicated on one-dimensional (1D) radiative transfer (RT) theory. We therefore always need to worry about the resulting forward signal model error. It needs to be quantified and, if possible, mitigated. Computational 3D RT has been brought to bear on this issue for decades, with 3D cloud models that have evolved from simple shapes such as cuboids and spheroids to deterministic fractal geometries on to stochastic multifractal distributions of scattering particle density that realistically mimic turbulent flows. More recently, computational fluid dynamics have been applied to cloud-scale process modeling with spectacular success, especially using Large-Eddy Simulation (LES) techniques. It was just a matter of time before this LES-based cloud modeling would be combined with 3D RT, on the one hand, to assess the visual verisimilitude of the synthetic clouds and, on the other hand, to apply the whole high-fidelity simulation framework to challenging problems in remote sensing.

We will report on three projects that use the "LES + 3D RT" toolbox at JPL. They cover the two broad categories of 3D RT issues: sub-pixel variability and cross-pixel radiative exchanges. Non-imaging (single-pixel) instruments, such as the Aerosol Polarimetric Sensor (APS) on the (doomed) Glory mission, only has the former problem. Airborne imagers, such as the Multi-angle Spectro-Polarimetric Imager (MSPI) with very high spatial resolution are affected by the later.

We used LES clouds and a proprietary Monte Carlo 3D RT model to explore the non-linear mixing of aerosol and broken cumulus cloud signals in the APS footprint (~10 km) over a wide range of viewing angles. We used the same LES clouds and an open-source deterministic 3D RT model to demonstrate 3D cloud reconstruction using a new kind of tomography, and then applied it to clouds captured with AirMSPI multi-angle/multi-pixel data. Finally, we retrieve from AirMSPI images of marine stratocumulus the radiative smoothing scale (where pixel cross-talk becomes less significant), and describe a path toward a robust retrieval of optical and geometrical thicknesses.

Keywords: Clouds, Aerosols, Large eddy simulation, Three-dimensional radiative transfer, Inverse problems, Remote sensing


3D RT … and 1D RT
VZA=0.0, phi=0
VZA=64.0
Nadir view
Oblique view
No shadows!
No cloud sides!

Analysis of optimal conditions for photo-based 3D modeling of cloud-like objects

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Currently, short-term rain/snow forecast is largely based on weather radars that observe rain/snow particles in the air and therefore cannot fully cover the clouds which may cause severe weather. New radars have recently been developed to detect clouds but the construction and maintenance of radars would be expensive. In order to develop low-cost methods to observe clouds, images of clouds captured with digital cameras could be used to locate and make measurements of clouds. Previous studies attempted to calibrate cameras using various objects and landmarks, such as topographic features, locations of airplanes and stars. However, for the practical cloud monitoring, it is important to develop methods to observe clouds without any external calibration but the proper photographic conditions for the task are yet to be carefully examined.
In order to examine the optimum conditions, images of the cloud-like objects, a lump of cotton and a piece of clay, were taken from different angles with digital cameras (Nikon D5500). The images were then processed by the 3D modeling software PhotoScanPro to construct a 3D model with which the location and size of the objects will be calculated. Up to now (15 Feb 2017), several preliminary experiments have been conducted. Using a lump of cotton hung with thin threads, images were captured with different dihedral angle between cloud-camera planes (θ = 1º, 2º, 3º… as indicated in Fig 1) to examine the viability to construct 3D models (A) and the accuracy of the calculated distance (B) and the surface area (C) of the models. Another experiment was held by capturing all-round photos of a piece of clay to generate a 3D model and examine the accuracy of volume measurements (D). Finally, using the cotton, multiple photos were captured with different positions of light source to evaluate the influence on the resulting models (E).
The results of the experiments are as follows: (A) although it varied depending on the number of photos, there was a maximum angle with which a 3D model could be made. The angle got the bigger the more photos were used. (B) Also, with the larger dihedral angles, the accuracy of the calculated distances improved and (C) the surface areas of the produced 3D models expanded. (D) In the second experiment, the calculated volume of the clay was about 30% smaller than the actual volume. This is most likely because the shaded bottom side of the clay made the model incomplete and this issue could be solved by changing the exposure of the camera. (E) The final experiment regarding the light source positions gave an outcome that the resulting 3D models were not very different with different positions of the light.
From the results of the experiment, we have found some of the optimum conditions. For further investigation, we will look into other conditions such as the number of cameras, elevation angle of cameras, size of the object taking up each image, and camera exposure to see if they affect the accuracy of resulting 3D models and measurements. We are also planning to take actual photos of clouds and generate 3D models using them in order to evaluate the validity of the preliminary experiments. In the end, by applying those conditions to the actual photo-capturing situation, consecutive images will repeatedly be captured to construct 3D models, the accumulation of which could help determine criteria for precipitation forecast.

Keywords: Cloud Observation, 3D Modeling, Camera Images, Precipitation Forecast

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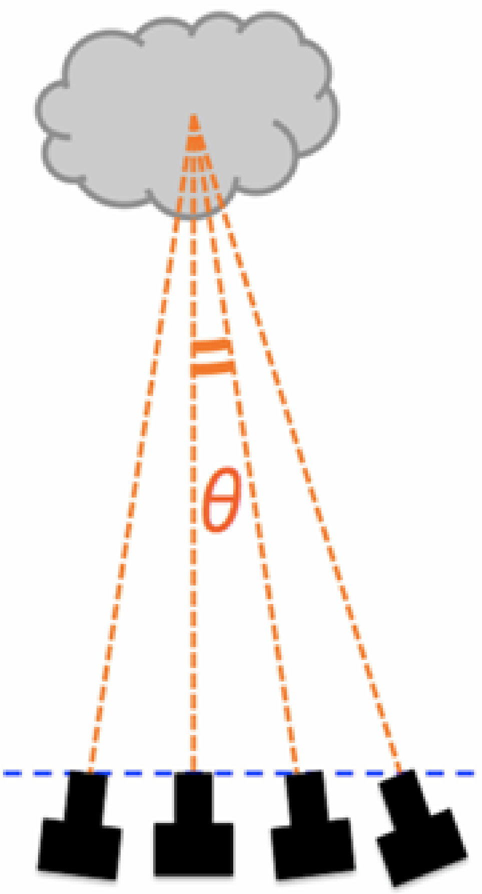

Variational Iteration Method for Infrared Radiative Transfer in a Scattering Medium

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A new scheme is proposed for using the variational iteration method (VIM) to solve the problem of infrared radiative transfer in a scattering medium. This scheme allows the zeroth-order solution to be identied as the absorption approximation and the scattering effect is included in the first-order iteration. The upward and downward intensities are calculated separately in the VIM, which simplies the calculation process. By applying the VIM scheme to two single-layer scattering media and a full radiation algorithm with gaseous transmission, it is found that the VIM is generally more accurate than the discrete-ordinates method (DOM), especially for cirrostratus. Computationally, the VIM is slightly faster than the DOM in the two-stream case but more than twice as fast in the four-stream case. In view of its high overall accuracy and computational efficiency, the VIM is well suited to solving infrared radiative transfer in climate models.

Keywords: Variational Iteration Method, Radiative Transfer, Absorption Approximation