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CONVENTIONAL CLEAR-SKY AEROSOL RETRIEVALS: DO THEY WORK FOR CLOUDY DAYS?

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ABSTRACT. This presentation highlights different approaches to determine the aerosol properties between clouds and covers a broad range of related topics, including the passive aerosol remote sensing from space, in situ observations of aerosol aloft and at surface and numerical modeling of aerosol and cloud properties. Some of these approaches, which are still in research phase, can reduce substantially the impact of cloud-induced contamination on the cloudy-sky aerosol retrievals, while other can reduce uncertainties associated with aerosol hygroscopicity and enhanced relative humidity near cloud edges. The combination of these approaches for addressing outstanding issues of the cloudy-sky aerosol retrievals is also discussed.

1. Introduction

Over the last several decades, progress has been achieved in the development of long-term records of basic clear-sky aerosol properties, such as the Ångström exponent and wavelength-dependent aerosol optical depth (AOD), through the use of the Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging SpectroRadiometer (MISR) [1, 2, 3]. The AOD is a measure of the total column aerosol burden, while the Ångström exponent is a clue to the aerosol size distribution. An increasing need for a better understanding of the complex aerosol-cloud interaction [4] has stimulated numerous studies aimed to obtain these column-integrated aerosol properties for partly cloudy regions. However, an extension of existing clear-sky aerosol retrievals to cloudy-sky conditions represents a great challenge due to the two main issues associated with (i) the cloud adjacency effects [5, 6] and (ii) large variations of relative humidity (RH) under partly cloudy conditions and simplified assumptions about RH in aerosol retrievals [7]. Below, we outline these issues and discuss how the cloudy-sky aerosol retrievals can be improved.

2. Cloud Adjacency Effects

The cloud adjacency effects are associated with the complex three-dimensional (3D) radiative effects of clouds [8], and their impact on passive aerosol retrievals can be outlined as follows. Scattering of solar light by clouds makes a nearby clear patch look brighter than would otherwise occur. Cloud-induced brightening can be responsible for large (up to 140%) errors of the retrieved AOD [5, 6]. The partial reduction of these effects can be performed using recently suggested approaches based on either the conditional sampling [5, 6], parameterization of 3D effects [9], or multi-spectral processing [10] techniques.

When conditional sampling is applied, only clear pixels located far away from clouds or shadows with relatively small cloud-induced brightening are selected [5, 6]. Such pixel selection involves statistical analysis of the two-dimensional (2D) horizontal distribution of reflectances, and provides a population of appropriate clear pixels, which depends on the cloud amount. For typical observational conditions with moderate (˜0.5) cloud fraction (CF), this population is quite small (less than 5% of total number of clear-sky pixels). The second approach involves the parameterization of the 3D radiative effects of clouds on the domain-averaged AOD retrievals [9]. This parameterization requires several cloud parameters, such as CF, domain-averaged cloud optical depth (COD), and the ratio of cloud thickness to cloud horizontal size, the so-called cloud aspect ratio. For a given scene, the MODIS Cloud Product (MOD06) can offer the first two parameters (CF and COD), but not the cloud aspect ratio.

The multi-spectral processing exploits reflectance ratios, which are less sensitive to the 3D effects of clouds than the reflectances themselves [10]. This technique, the so-called the reflectance ratio (RR) method, provides an effective way to reduce substantially the impact of the 3D effects on the retrieved AOD. Using a sensitivity study, Kassianov et al. [11] demonstrated that the RR method has the ability to detect both "remote" and "nearby" clear pixels appropriate for the RR-based AOD retrievals. Compared to the conditional sampling, such detection does not require the statistical analysis of the 2D horizontal distribution of reflectance and increases by several times the number of appropriate pixels where AOD retrieval is possible. Also, the sensitivity study suggested that the RR-based detection of clear pixels and the accuracy of AOD retrievals are not sensitive to the domain-averaged COD. The ability of the RR method to retrieve AOD from high-resolution aircraft observations has been demonstrated recently by a case study [12].

3. Relative Humidity Effects

Changes of RH determine the enhancement in light scattering due to the uptake of water vapor by hygroscopic particles. Therefore, inappropriate or inaccurate specification of RH can be responsible for large uncertainties in the assumed aerosol optical properties, and consequently, in the corresponding aerosol retrievals. These retrievals are based on several assumptions. A fixed RH is one of them, and its application can lead to large (up to 40%) errors in the retrieved AOD even under cloud-free conditions [7]. Since clouds transport moisture, enhanced RH is typically observed near cloud edges and cloudy-sky days are characterized by large spatial and temporal changes of RH when compared to the clear-sky conditions. Therefore, the corresponding cloudy-sky AOD errors associated with simplified assumptions about RH can exceed significantly their clear-sky counterparts. To reduce these errors, both aerosol hygroscopicity and changes of RH over the atmospheric column should be taken into account. We emphasize that the aerosol hygroscopicity is a function of the aerosol chemical composition, the latter is critical for examining the humidification impact on the aerosol retrievals.

Aerosol optical and chemical properties are commonly measured by research aircraft. One of them, the U.S. DOE Gulfstream-1 (G-1) was configured to make *in situ* measurements of the chemical and optical properties of aerosols, cloud microphysics, trace gas concentrations and meteorological variables during the Cumulus Humilis Aerosol Processing Study (CHAPS) that was conducted in June of 2007 near Oklahoma City, USA [13]. Two separate inlets, an isokinetic and counterflow virtual impactor, were used to measure the aerosol chemical composition. In particular, analysis of these measurements suggests that the fractional amount of sulfate relative to the other components was smaller and the fractional amount of organics was larger downwind of Oklahoma City. In other words, a large fraction of the particle mass produced near Oklahoma City was organic. Also, analysis of integrated data set of aerosol and cloud properties collected by G-1 demonstrates that pollution had a measurable impact on the cloud optical properties and provides evidence of the so-called first aerosol indirect effect in continental shallow cumuli [14].

Models with an improved description of cloud-aerosol interactions have been used successfully to examine the complex cloud-aerosol processes and their interactions, including variations of RH and the corresponding changes of cloudy-sky aerosol optical properties. To illustrate the effect of the RH on the cloudy-sky aerosol extinction coefficient and AOD at 500 nm, we use two outputs from a large-eddy simulation cloud model [15] adjusted to boundary layer water clouds. The simulation is performed for a typical cloudy day observed during CHAPS. The simulated horizontally averaged RH increases from 60% near the surface to the 86% maximum at the cloud base (˜1 km), than it decreases again to below 50% above 3 km. The first output is obtained using the actual predicted RH at every grid point. The second output is defined applying the minimum RH found at each level. The comparison of these two outputs suggests the following. At the cloud base level, the enhanced humidity can increase aerosol extinction coefficient substantially (by up to 40% on average). However, the overall impact of the RH on the column-integrated AOD is much smaller (about 10% increase).

4. Summary

Issues associated with (i) the cloud adjacency effects [5, 6] and (ii) large variations of RH and simplified assumptions about RH represent a great challenge that the aerosol remote sensing faces today. To minimize impact of the cloud adjacency effects on the aerosol retrievals, three different but overlapping approaches have been suggested recently. They apply the conditional sampling, parameterization of 3D effects, and multi-spectral processing, respectively. The performance of these approaches has been demonstrated successfully using numerical models, and such modeling capabilities should be continued and expanded in future studies. The reduction of the potentially large uncertainties associated with the aerosol hygroscopicity and large variations of RH requires additional information about RH, particle type and chemical composition. Active aerosol remote sensing [16, 17], ground-based retrievals [18], *in situ* observations [13] and detailed model simulations [19] together can provide the requested information. Thus, a greater integration across the aerosol remote sensing, *in situ* measurements and model simulations is required to address these outstanding issues properly.

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