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Understanding uncertainties in the retrieval of polar mesospheric clouds from the cloud imaging and particle size experiment in the presence of a bright Rayleigh background

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ABSTRACT

This paper presents a framework for understanding and quantifying the leverage available for inverting the radiance signal in order to retrieve particle size distribution mode radius and albedo from polar mesospheric clouds (PMC) observations using the cloud imaging and particle size (CIPS) instrument on board the aeronomy of ice in the mesosphere (AIM) satellite. The observed signal is a superposition of the scattering angle dependence of the cloud albedo and the Rayleigh scattered albedo controlled by ozone at the stratopause. The leverage as is defined in the paper is a way to quantify how much the net scattering angle dependence changes as a function of mode radius. The leverage is determined by decomposing the observed signal into orthogonal components which isolate the parts of the signal that are unique to changes in mode radius from those that could be due to changes in the background. This leverage is considered along with instrument noise performance to determine retrieval uncertainties and to understand minimum thresholds in the cloud retrieval parameters.

1. Introduction

The aeronomy of ice in the mesosphere (AIM) satellite is the first satellite dedicated to the study of polar mesospheric clouds (PMC) [Russell et al., 2009]. The satellite is in a sun synchronous orbit with an approximately noon local time equator crossing. The cloud imaging and particle size (CIPS) instrument is a four camera UV imaging array with a wide field of view centered in the nadir. The field of view encompasses 60° from nadir along track (~2000 km) by 40° cross track (~1000 km) at a nadir resolution of 1 km by 2 km, respectively. In order to minimize the Rayleigh scattering component of the signal, the instrument observes at 265 nm [McClintock et al., 2009]. This wavelength is strongly absorbed by ozone.

The goal of CIPS is to provide global albedo and mode radius maps of PMC at high horizontal resolution [Rusch et al., 2009]. Many instruments can be used to infer albedo and mode radius, and some of those instruments provide better leverage on that information than CIPS, but no instrument has this information at such high horizontal resolution with near global coverage. With the horizontal maps one can study gravity waves which play an important role in creating the environment for the clouds to exist through gravity wave forcing of the mean flow, but they also perturb the clouds locally which allows for their observation in CIPS data [Chandran et al., 2009, 2010; Taylor et al., 2011]. The maps are also useful for adding information on the horizontal structure to the temporal information in coincident lidar observations [Baumgarten et al., 2012].

Each air parcel in the map is observed several times with different scattering angles as AIM passes over it. This scattering angle dependence for each parcel is called the “scattering profile”. The scattering angle dependence of the observed albedo is a result of Rayleigh scattering by the atmosphere and the ice scattering phase function of the PMC. The magnitude and angular dependence of the PMC phase function depends on the albedo and mode radius of the particle size distribution for the observed cloud, so analysis of this scattering angle dependence allows for retrieval of the albedo and mode radius maps. The magnitude of the change in the scattering profile angular dependence as a function of mode radius is quantified using its “leverage” which will be defined in Section 4.3. The details of the algorithms used to produce these maps have been published for the operational CIPS retrieval, version 3, in Bailey et al. (2009) and for version 4 in Lumpe et al. [this issue]. This paper instead takes a step back and attempts to provide an understanding and quantification of the some of the key uncertainties in the CIPS measurement. How much leverage

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on the mode radius of the cloud particles does the measurement really have? Is the mode radius inversion unique? How bright must a cloud be in order to be retrievable using CIPS measurements, and how does one define its brightness from the standpoint of the ability to retrieve its properties? How do the leverage and minimum brightness change as a function of solar zenith angle, sampling and mode radius? This paper attempts to answer the above questions and to provide a frame work for visualizing and diagnosing the impact of errors on the CIPS retrieval.

In Section 2 we start by describing the CIPS scattering profile and the difficulties involved in separating the cloud signal from the Rayleigh signal. In Section 3 the scattering profile is transformed using orthonormal basis vectors which clearly separate the portion of the scattering profile that is exclusively due to the cloud and that which is consistent with both clouds and a Rayleigh background. In Section 4 the retrieval problem is analyzed using the transformed signal. In this section many of the questions above are answered. Finally in Section 5, simulated retrievals are done in the presence of noise, and the results of the simulation are checked for consistency with expectations based on the conclusions drawn in Section 4.

2. The CIPS scattering profile

2.1. Models

The CIPS instrument observes air parcels at several different scattering angles as AIM passes overhead. These observations create a scattering profile which includes the scattering angle dependence of cloud ice albedo near 83 km and Rayleigh scattered sunlight from about 50 km. The Rayleigh scattering component of the scattering profile (referred to as the “background”) obeys the nearly symmetric Rayleigh scattering phase function. The cloud particles are larger in comparison to the observed wavelength, so their scattering is not symmetric in scattering angle with much stronger efficiency for forward scattering. Fig. 1 is an example modeled scattering profile illustrating the components of a CIPS signal. The albedo is expressed in the unit $10^{-6}\,\mathrm{sr}^{-1}$ (G) which will be used throughout this paper. Note that the Rayleigh component is not perfectly symmetrical. While the Rayleigh scattering phase function is almost perfectly symmetric about 90° scattering angle, the observed albedo is also a function of the path geometry through the atmosphere which causes a slight asymmetry; however, it is significantly less than the asymmetry in the cloud component of the signal.

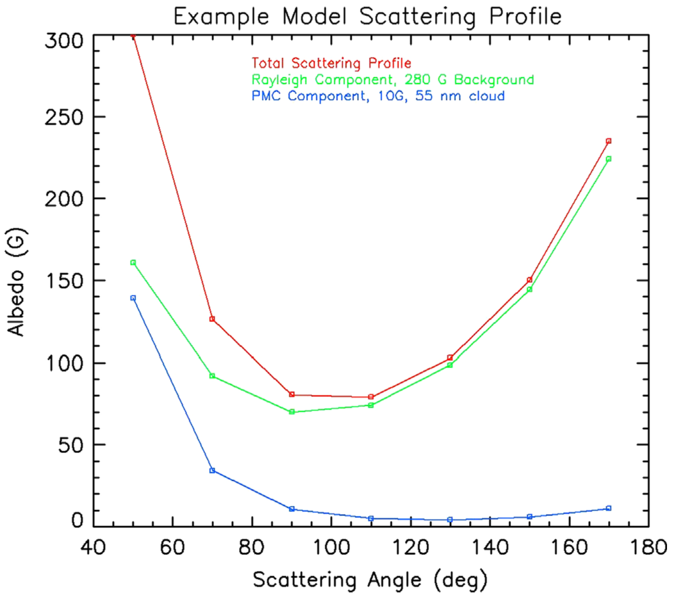

Fig. 1. A simulated CIPS scattering profile. The red curve is what would be observed and the green and blue curves are the Rayleigh and PMC components, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

For this analysis, an analytical model which describes the Rayleigh scattering background albedo, $R(\theta,\mathrm{SZA},\mathrm{VWA},C,\sigma)$, is used [Mcpeters, 1980; Bailey et al., 2009]. We will refer to this model as the “C–σ model”. The model is used in the following form,

$$R = C\,P(\theta)\frac{\{[Chap(\mathrm{SZA})+Chap(\mathrm{VWA})]/2\}^{-\sigma}}{\cos(\mathrm{VWA})}, \tag{1}$$

where $P(\theta)$ is the Rayleigh scattering phase function as a function of the scattering angle θ, $Chap(\mathrm{SZA})$ is the Chapman (1931) function as a function of the solar zenith angle SZA, VWA is the angle between the zenith at the observation point and the line of sight (referred to as the viewing angle hereafter) and σ is the ratio of the ozone scale height to the atmospheric scale height. The Chapman function is calculated using the asymptotic expansion method of Huestis (2001). The C parameter is the phase adjusted albedo one would observe if the parcel were to be viewed in the nadir at the sub solar point. This form is convenient for fitting since the C parameter is simply a scale factor on the Rayleigh scattering profile; however, the model is usually parameterized in terms of the ozone column density at an altitude close to the peak of the altitude contribution function in place of the C parameter used here. For a physical interpretation, it is approximately proportional to the atmospheric pressure level at which the ozone optical depth reaches 1 [Bhartia et al., 1996].

The model makes several simplifying assumptions to make the problem solvable analytically. One of the most significant of these assumptions is that σ is constant with height. This is generally not true; however, the contribution to the albedo with altitude is sharply peaked (approximately 15 km FWHM) near 50 km, where the optical depth is approximately one. The column density and σ must represent the values near the peak of this contribution for the model to be accurate. For cloud retrieval purposes though, the model simply needs to be able to fit the observed background so that it can be removed, and it is able to do this to approximately the 2% level. The residual difference is very systematic, and it is parameterized and removed in the version 4 retrieval algorithms using “error maps” [Lumpe et al., this issue].

The cloud scattering phase functions are simulated using the T-matrix codes of Mishchenko and Travis (1998). The particle size distributions are assumed to be Gaussian with widths equal to 0.355 (instead of 0.39 used in the version 4 algorithm [Lumpe et al., this issue]) times the mode radius, r, up to a maximum width of 16 nm at which point the width is held constant. Since in this paper the radius of individual particles is rarely discussed, “radius” will often be used in place of mode radius for brevity. In instances where the mode radius is not what is being referred to, this will be made clear. The axial ratio of the cloud particles is assumed to be two. An additional $1/\cos(VWA)$ factor is added to account for the increased line of sight path length through the cloud with increasing VWA. The cloud albedo A is defined as the albedo one would observe if viewing the cloud in the nadir with a scattering angle of 90°. Apart from the Gaussian width, these are the same models and assumptions used for the operational CIPS retrieval. The fact that the Gaussian width is slightly different is due to it being chosen at a time prior to when the operational number was finalized. It is of little consequence to the results derived in this paper.

2.2. Radius/background ambiguity

When looked at in the absence of a Rayleigh background, the cloud scattering phase functions of different radii look very different. The most notable difference is that the asymmetry, where forward