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Comparing nadir and limb observations of polar mesospheric clouds: The effect of the assumed particle size distribution

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ABSTRACT

Nadir viewing observations of Polar Mesospheric Clouds (PMCs) from the Cloud Imaging and Particle Size (CIPS) instrument on the Aeronomy of Ice in the Mesosphere (AIM) spacecraft are compared to Common Volume (CV), limb-viewing observations by the Solar Occultation For Ice Experiment (SOFIE) also on AIM. CIPS makes multiple observations of PMC-scattered UV sunlight from a given location at a variety of geometries and uses the variation of the radiance with scattering angle to determine a cloud albedo, particle size distribution, and Ice Water Content (IWC). SOFIE uses IR solar occultation in 16 channels (0.3–5 μm) to obtain altitude profiles of ice properties including the particle size distribution and IWC in addition to temperature, water vapor abundance, and other environmental parameters. CIPS and SOFIE made CV observations from 2007 to 2009. In order to compare the CV observations from the two instruments, SOFIE observations are used to predict the mean PMC properties observed by CIPS. Initial agreement is poor with SOFIE predicting particle size distributions with systematically smaller mean radii and a factor of two more albedo and IWC than observed by CIPS. We show that significantly improved agreement is obtained if the PMC ice is assumed to contain 0.5% meteoric smoke by mass, in agreement with previous studies. We show that the comparison is further improved if an adjustment is made in the CIPS data processing regarding the removal of Rayleigh scattered sunlight below the clouds. This change has an effect on the CV PMC, but is negligible for most of the observed clouds outside the CV. Finally, we examine the role of the assumed shape of the ice particle size distribution. Both experiments nominally assume the shape is Gaussian with a width parameter roughly half of the mean radius. We analyze modeled ice particle distributions and show that, for the column integrated ice distribution, Log-normal and Exponential distributions better represent the range of masses that contribute to the IWC. We further show that agreement between SOFIE and CIPS is further improved with the assumption of either Log-normal or Exponential ice particle size distributions. This improvement suggests that the range of mass bearing particle radii is larger, but not significantly shifted from what is obtained by assuming a Gaussian distribution. The assumption of an Exponential particle size distribution, as shown to be justifiable here, has the attractive benefits of being characterized with a single parameter, the mean radius, which greatly facilitates studies of the spatial and temporal variation of PMC particle size distributions as well as comparisons between observations and models. Overall, our results represent a validation of both the CIPS and SOFIE datasets.

1. Introduction

Polar Mesospheric Clouds (PMCs) have received a great deal of attention in recent years with extraordinary progress in their observation and modeling. Progress in microphysical modeling (Rapp

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and Thomas, 2006) has led to global models that include ice microphysics to varying degrees (Berger and Lübken, 2006; Merkel et al., 2009; Bardeen et al., 2010). Such comprehensive models are now beginning to reproduce the long-term increases in PMC occurrence rate and brightness (Lübken et al., 2009; Lübken and Berger, 2011) that have been observed from satellite (DeLand et al., 2003, 2006, 2007). These modeling improvements are contemporaneous with new and improved observations from the ground (Chu et al., 2003; Fiedler et al., 2003; Baumgarten et al., 2010) and from space (DeLand et al., 2003; Eremenko et al., 2005; Karlsson and Gumbel, 2005; von Savigny et al., 2005; 2009; Rusch et al., 2009; Hervig et al. 2009a).

While there have been great improvements in modeling the bulk properties of PMC ice and its long term variation, observing the microphysical properties of the ice has proven difficult. Several experiments produce ice particle size data products (Bailey et al., 2009; Lumpe et al., 2013; Eremenko et al., 2005; Hervig et al., 2009a, 2012), yet there is not wide agreement on the magnitude and variability of PMC particles sizes. The most common assumption regarding the shape of the Ice Particle Size Distribution (IPSD), that of a Gaussian with prescribed relationship between the mean radius and width (Baumgarten et al., 2010), has not been validated.

The Aeronomy of Ice in the Mesosphere (AIM) satellite was launched in April of 2007 and has been observing PMCs since then. Russell et al. (2009) provide an overview of the mission, its objectives, and initial results. Included on AIM are two instruments: the Cloud Imaging and Particle Size (CIPS) instrument (Rusch et al., 2009) and the Solar Occultation for Ice Experiment (SOFIE) (Gordley et al., 2009). CIPS images PMCs in the nadir and through angular variation of the observed radiance, provides particle size information in addition to cloud brightness, reported as albedo in units of $10^{-6}\ sr^{-1}$ (symbolized as G), and column ice mass, reported as Ice Water Content (IWC) in units of $g\ km^{-2}$ (Lumpe et al., 2013). SOFIE measures ice properties including particle size as well as ice and air temperature, water vapor abundance, and other key species all as a function of altitude through solar occultation (Hervig et al., 2009a). CIPS observes the entire polar cap with a nominal spatial resolution of about $5 \times 5\ km^2$. SOFIE is much more sensitive and has more observational leverage than CIPS on obtaining IPSD information, but is very limited in spatial coverage due to the solar occultation technique.

In this paper we compare Common Volume (CV) observations by CIPS and SOFIE. A key goal of that comparison is mutual validation of the two datasets. In accomplishing that validation, we seek to test a key assumption used in interpreting observations from both experiments, the shape of the IPSD. To date, no experiment has directly measured the PMC IPSD. It was long assumed that the particle size distributions were best represented by a Log-normal distribution (Thomas and Mckay, 1985; von Cossart et al., 1999). Model distributions from Rapp and Thomas (2006) suggested the true distribution, even when vertically integrated, was more closely described by a Gaussian distribution and that Log-normal distributions severely overestimate the abundance of larger particles. Since their work, the assumption of a Gaussian IPSD has been common-place in interpretation of PMC observations, with particle size data products generally consisting of the parameters of a Gaussian distribution: mean radius, width parameter, and number density of particles. Most PMC observing instruments do not produce enough information to uniquely determine both the mean radius and width parameter, and so a relationship between the two is generally prescribed. Baumgarten et al. (2010) suggested the width parameter is approximately 0.4 times the mean (see Section 2.2 for the exact relationship). This assumption is used by a number of experiments (Lumpe et al., 2013; Hervig et al., 2012). Because there is currently no viable technique for measuring the IPSD directly, there has as yet been no challenge to the assumption of a Gaussian distribution.

In this work we compare particle size data products from CIPS and SOFIE, two remote sensing instruments observing the same volume of ice from the same platform, but using very different techniques with very different geometries and wavelengths. To achieve agreement between the two experiments is not only a powerful validation of each approach, but also of the assumption underlying both experiments – the shape of the IPSD.

The paper proceeds as follows. We begin with an examination of model results that challenge the common assumption of a Gaussian IPSD. Following that discussion is an overview of CIPS and SOFIE and their data processing algorithms. The CIPS and SOFIE common volume observations are then described and compared.

2. The shape of modeled ice particle size distributions

2.1. Model calculations

Before making any comparisons between CIPS and SOFIE, we first motivate the study of different IPSD assumptions through examination of modeled IPSD. To do so, we examine a collection of model-generated, vertically-integrated IPSD profiles. We fit each of those column IPSD to three proposed functional forms, and then analyze the results to assess the reasonableness of each of the functional forms. We choose the vertically integrated IPSD because that is what CIPS observes as discussed in Section 3. It should be borne in mind that any conclusions we form in this paper are limited to the vertically integrated IPSD and may not apply to smaller observing volumes.

We examine 4800 modeled altitude profiles of IPSD generated by the model of Bardeen et al. (2010). This model is the combination of the Whole Atmosphere Community Climate Model (WACCM) (Garcia et al., 2007), a chemistry-climate model, and a microphysics model based on the Community Aerosol and Radiation Model for Atmospheres (CARMA) (Turco et al., 1982; Toon et al., 1988; Jacobson et al., 1994) referred to as the WACCM/CARMA model (Bardeen et al., 2008). The model includes Brownian diffusion of particles at high altitudes as well as the nucleation, deposition, and sublimation of ice particles in the mesosphere. Advection, eddy diffusion and wet deposition of meteor smoke particles, sedimentation, and coagulation are also included. The model uses a horizontal resolution of $4° \times 5°$ and a vertical grid with 125 levels and ~0.35 km spacing near the mesopause. WACCM incorporates a gravity wave parameterization (Sassi et al., 2002; Garcia et al., 2007) to include the effect of vertically propagating gravity waves generated in the troposphere upon the model's atmospheric circulation. See Bardeen et al. (2010) for details. CARMA fully interacts with the water vapor from the WACCM model, so for each model time step the water vapor from WACCM is passed into CARMA and any changes to water vapor from deposition or sublimation are then passed back to WACCM. The total amount of water vapor in WACCM is then adjusted accordingly. The initial condition for all simulations uses a steady state meteoric smoke distribution from the fourth year of a WACCM/CARMA meteoric smoke simulation (Bardeen et al., 2008). The supply of smoke particles is refreshed with a horizontally and temporally uniform meteoric influx of ~16 kt/yr (Hughes, 1978), using an ablation profile by Kalashnikova et al. (2000), which has a peak production rate at ~85 km. For ice particles the (spherical) particle radius range is 0.2 nm to 348 nm. The model runs used in this paper have a smaller logarithmic size grid, with a particle volume ratio of 1.61 between bins, and a total of 48 bins (compared to 28