OPTICAL-MICROPHYSICAL MODELING OF A SYNOPTICALLY FORCED CIRROSTRATUS

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ABSTRACT

A model is presented that permits the simulation of the optical properties of cirrus clouds as measured with depolarization Raman lidars. The model is applied to the measurement of an Arctic cirrus cloud. Good agreement between simulations and lidar observations is found. Sensitivity tests suggest that the parameterization of the mass fraction of plate-like cloud crystals is preferably done in terms of the ambient rather than the nucleation temperature. Furthermore, model runs that include horizontal alignment of ice particles yield the best results, better than those with randomly oriented polycrystals.

1. INTRODUCTION

Reference [1] explained measurements of Arctic cirrus clouds with a depolarization Raman lidar in terms of size, shape and growth of the cirrus particles. The analysis was based on theoretical particle optical data. The direct approach to testing this newly developed retrieval method would be to check the retrieval results against in situ measurements (as it was done by, e.g., [2]-[4]), however, this is not possible in this case because cirrus sampling was not performed during the lidar measurements. Therefore a different line of approach is pursued here: A cirrus model with explicit microphysics [5] is employed to simulate the geometrical evolution of the ice cloud, the microphysical data are then converted to cirrus optical properties based on the interpretation of [1], and finally synthetic optical data and lidar observations are compared. Certainly, the analysis presented in this study cannot be regarded as a substitute for field campaigns combining remote and in situ observations, but it is useful to test whether the interpretation of the lidar data is plausible, to define parameter spaces, to point at deficiencies, and, if convincing agreement is achieved, to support the basic concept.

In section 2, a brief summary of the optical-microphysical model is presented. In section 3, three basic types of model scenarios based on different hypotheses on particle properties are discussed. Particle morphological complexity and particle preferred orientation are taken into account, which have not been included in an earlier study [6]. Finally, the optical-microphysical model is applied to the measurement of an Arctic cirrus cloud on 16 January 1997 (section 4). Emphasis is put on the intercomparison of modeled and measured optical properties; the sensitivity tests that were performed to correctly reproduce the spatial and temporal evolution of the ice cloud were published previously [5].

2. OPTICAL-MICROPHYSICAL MODEL

Fig. 1 is a schematic of the coupled optical and microphysical cirrus model. In the two independent iterative processes, the lidar measurements are used to optimize cloud modeling. In a first process, cirrus microphysics are simulated as a function of height and time. Model output also includes the nucleation temperature distribution of the cirrus particles. Meteorological data that are input to the microphysical model are profiles of temperature, humidity, and vertical wind velocity. A first guess is derived from radiosonde and wind profiler measurements concurrent with the lidar observation, or from mesoscale simulations. The nucleation scheme is prescribed. Humidity, vertical wind velocity, and nucleation parameters are then deduced from sensitivity tests where the val-

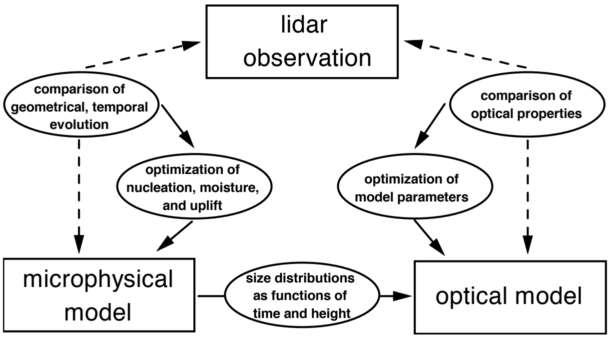

Fig. 1. Schematic of the optical-microphysical model.

ues selected yield the best agreement between (1) the observed and modeled temporal evolution of the cirrus cloud system (cloud height and vertical extent), and (2) the contours of the observed particle extinction profile and the modeled ice mixing ratio profile (which are assumed to be related). Best agreement was found for heterogeneous nucleation parameterized according to [7], and an updraft wind speed of 5 cm/s over 7 hours.

The time- and height-resolved microphysical data are then input to the optical model used for simulating the cirrus cloud as monitored with lidar. The particle size distributions are converted to cloud optical properties (including the lidar ratio and the depolarization ratio) by use of theoretical optical data obtained by ray-tracing computations [8]. Different model scenarios, and thus sets of model parameters, can be selected to study the dependence of the relationship between cloud optical and microphysical properties on the assumptions made about the (size- and temperature-dependent) morphology and spatial orientation of the ice particles. Optimum model scenario and parameters are found by comparison between observed and modeled cirrus particle optical properties.

3. MODEL SCENARIOS

Common to all model scenarios is how ice mass is split into the two principal particle shapes (columns and plates), and how the aspect-ratio to size relationship of the particles is treated. Cirrus particle sampling indicates a general tendency from plate-like crystals at warmer temperatures to column-like crystals at colder temperatures. For this reason, we introduce a partitioning function to split the modeled particle size distribution (simulated by the microphysical model) into two sub-populations of columns and plates. The function is one (plates only) at and above temperature T_{H} (subscript 'H' denotes habit) and falls off for colder temperatures with a gradient controlled by parameter c_{T}. Either the ambient temperature T_{A} or the nucleation temperature T_{N} can be chosen as the function's variable. Field studies also show that in natural ice clouds, the aspect ratio and maximum dimension of particles of the same principal morphology are connected. To model this observation, the parameterization of [9] is adopted with adjustments based on sensitivity tests. The model scenarios investigated in this study differ in the way the morphology of the particles and their orientation in space, random (3 D) or horizontal (2 D), are treated. Three different scenarios are studied.

3.1 Monocrystals in 3-D Orientation

The ice particles are assumed to be single crystals of either columnar or planar shape. Particle orientation is random. Model parameters are c_{T} and T_{H}; the name convention for this series of tests is M3D(c_{T}, T_{H})T_i, where T_i is either T_{A} or T_{N}.

3.2 Polycrystals in 3-D Orientation

Cirrus particles are often better described as clusters of basic crystals than as monocrystals. Under the assumptions that the basic crystals scatter independently (as is the case of spatial particles with long protruding extensions [10]) and show a narrow habit distribution, we can model the optical properties of morphologically complex particles by an optical break up of the crystal cluster. This is done by introducing function μ, $\mu \geq 1$, which is the ratio of the particle mass as determined with the microphysical model (monocrystals assumed) to the mass of the optically dominant basic crystal (the one with the largest scattering cross section). The optical properties of the cluster are then assumed to be identical with those of this basic crystal. Similarly to the mass fraction of plates, μ is either a function of T_{A}, or T_{N}, and depends on the two model parameters m_0 (the maximum number of basic crystals in a cluster) and m_{T} (the slope). Hence, the total number of model parameters is four. Particle orientation is random. The name convention for this series of tests is P3D(c_{T}, T_{H}, m_0, m_{T})T_i.

3.3 Monocrystals in 3-D or 2-D Orientation

Falling ice particles larger than a critical size ($d_{2\mathrm{D}}$) have a tendency to assume an orientation with their maximum geometrical dimension in the horizontal plane (2-D orientation). If the crystal faces of these 2-D-oriented particles are aligned horizontally, their optical properties, as observed with lidar, deviate significantly from those found for random orientation. However, this effect is less pronounced, or different, if the particles wobble, rotate about the center axis (columns) or have an intrinsic randomness (clusters). So the fractions of (optically) aligned columns and plates, $f_{2D,col}$ and $f_{2D,pla}$, can be expected to be small. The total number of model parameters is six, the notation is M2D3D(c_T, T_H, $d_{2D,pla}$, $f_{2D,pla}$, $d_{2D,col}$, $f_{2D,col}$)T_i.

4. 16 JANUARY 1997 CASE STUDY

On this day a synoptically forced cirrus cloud was observed for 7 hours above the Swedish research facility Esrange (67.9 °N, 21.1 °E) [5]. Three measurement intervals (0–29 min, 116–156 min, and 357–421 min after the start of the cloud event) were used in the optical-microphysical modeling effort (which are the same as in [1]). Fig. 2 compares the measured profiles of depolarization ratio and lidar ratio to those modeled under the assumption that the cirrus particles were monocrystals in random orientation (M3D scenario). Optimum model parameters were determined by the method of least squares. Only intervals 2 and 3 are shown because they are the most interesting. The M3D simulations can reproduce both optical properties in interval 2, but fail to model the lower part of the cirrus cloud in interval 3. The use of T_A instead of T_N yields better results for the depolarization ratio but not in the case of the lidar ratio. Here the discrepancy between measurement and simulations below 7 km shows that the assumption of randomly oriented monocrystals is insufficient to explain the optical properties of cirrus clouds.

The agreement in lidar ratio in interval 3 can be improved if polycrystals instead of monocrystals are assumed. Small crystals have smaller lidar ratios than large particles, and so an optical break up of a single crystal leads to the needed reduction in lidar ratio. The results for the P3D simulations are presented in Fig. 3. The optical properties of interval 3 are now better reproduced than in Fig. 2, yet the agreement in lidar ratio in interval 2 is less perfect. T_A is the better parameter for splitting the ice mass into plate-like and column-like particles (particularly for depolarization ratio), which indicates that the ambient conditions affect the optical properties of atmospheric ice particles more than those conditions that prevailed when the particle formed. Interestingly, an abrupt change in particle shape at temperatures between -35 and -40°C is required to simulate the steep gradients in depolarization ratio and lidar ratio at 6.5 km, which is in agreement with earlier observations [11].

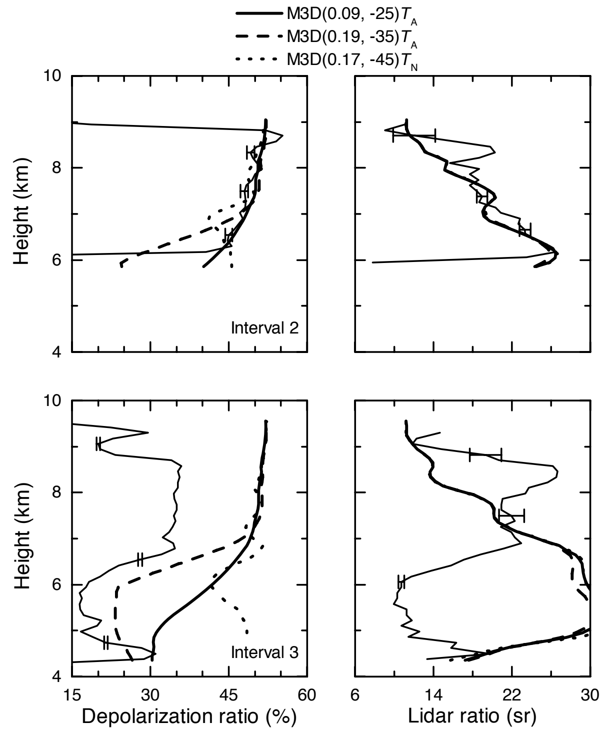

Fig. 2. M3D model results. Intervals 2 and 3 are, respectively, 40-min and 64-min observation periods about 2 and 6 hours after the start of the cloud event. Thin curves show the lidar measurements (with error bars). Model results for interval 1 (at start of cloud event) agree well with the observations in all cases (not shown).

The results of model runs with, in part, horizontally aligned ice crystals are highlighted in Fig. 4. The observations are better reproduced than with the polycrystal model scenario P3D (cf. Fig. 3), particularly the lidar ratio in interval 2 and both optical properties below 6.5 km in interval 3. Furthermore, to explain the measurements, it is sufficient to take 2-D orientation of only plates into account. Aligned columns are not required, a fact that effectively reduces the total number of M2D3D model parameters from six to four. When T_A is used to split the particle population into plates and columns, optimum values of T_H and c_T are -15°C and 0.05/°C. With these parameter values, the ambient temperature at which equal masses of plates and columns exist is about -25°C. Reference [12] observes a gradual change in basic habit from planar to columnar around the same temperature.

In summary, the 16 January 1997 case study shows that the optical-microphysical model simulates the lidar observations quite well. This is a remarkable result given the simplicity of the model and the relatively small numbers of model parameters. The sensitivity tests suggest that the parameterization of the mass fraction of plate-like cloud crystals is preferably

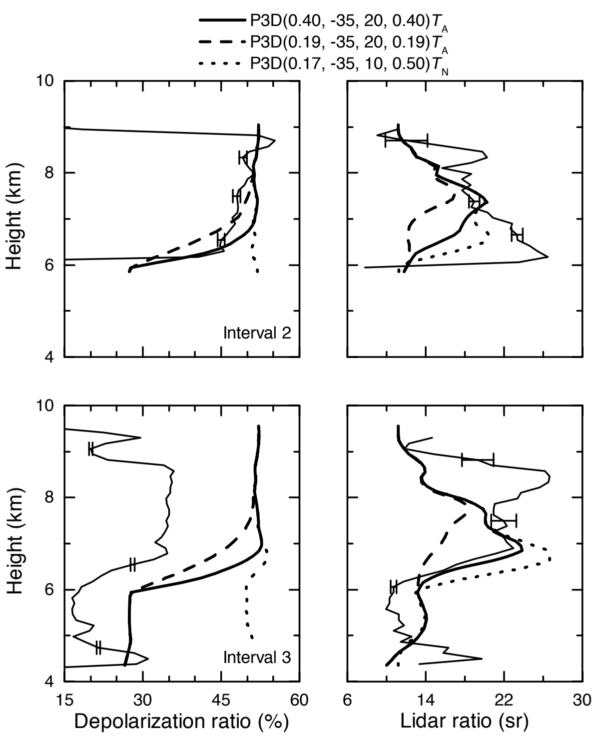

Fig. 3. P3D model results.

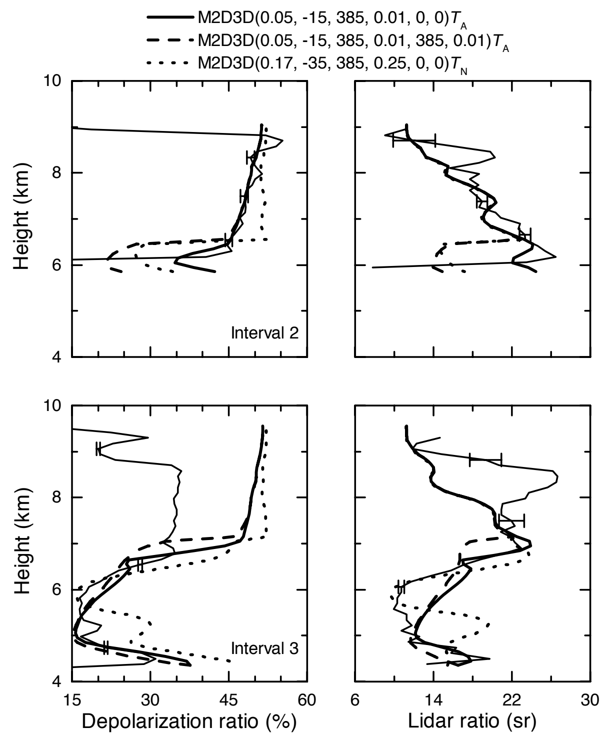

Fig. 4. M2D3D model results.

done in terms of the ambient rather than the nucleation temperature. Furthermore, simulations that include horizontal alignment of ice particles yield the best results, better than those with randomly oriented polycrystals. On-going work is dedicated to studying the effects of a parameterization of the fractions of basic crystal habits in terms of mean particle mass instead of temperature.

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