A User Guide to a Particle-Growth and Trajectory Model (Using One-Dimensional and Three-Dimensional Wind Fields)

J.L. Parrish
A.J. Heymsfield
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Data Used in Initial Mass Computation</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Equations Used in Terminal Velocity Calculations</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>List of Symbols</td>
<td>8-9</td>
</tr>
<tr>
<td>4</td>
<td>Equations Used to Iteratively Solve the Particle Temperature</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>Equations Used to Calculate the Ventilation Coefficient</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>Equations Used for Collection Efficiency Calculations</td>
<td>11</td>
</tr>
<tr>
<td>7</td>
<td>Accretional Density Parameterization</td>
<td>13</td>
</tr>
<tr>
<td>8</td>
<td>Conditions Defining the Habits</td>
<td>18</td>
</tr>
<tr>
<td>9</td>
<td>Equations for Calculating Temperature, Liquid Water Content, and Vertical Velocity Profiles</td>
<td>27</td>
</tr>
<tr>
<td>10</td>
<td>Specifications of Droplet Size Distribution and the Liquid Water Content</td>
<td>29</td>
</tr>
<tr>
<td>11</td>
<td>Specifications of Growth Model Test Set</td>
<td>46</td>
</tr>
</tbody>
</table>
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Diagram of Development of Different Particle Types in Dry Growth</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>Iterative Approach to Transitions between Habits</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>Parameter Plots Showing the Transition Paths of a Particle Changing Habits</td>
<td>21-22</td>
</tr>
<tr>
<td>4</td>
<td>Example of Trajectory Printout</td>
<td>37</td>
</tr>
<tr>
<td>5</td>
<td>Example of Microfilm Output of Trajectory Listings</td>
<td>38</td>
</tr>
<tr>
<td>6</td>
<td>Examples of Trajectory Plots</td>
<td>40</td>
</tr>
<tr>
<td>7</td>
<td>Example of Perspective Plot</td>
<td>41</td>
</tr>
<tr>
<td>8</td>
<td>Examples of Time Plots</td>
<td>42</td>
</tr>
<tr>
<td>9</td>
<td>Examples of Level Plots</td>
<td>44</td>
</tr>
<tr>
<td>10</td>
<td>Examples of Initial- and Final-Position Plots</td>
<td>45</td>
</tr>
<tr>
<td>11</td>
<td>Pictures of a Capped Column and a Capped Bullet Rosette</td>
<td>48</td>
</tr>
</tbody>
</table>
ABSTRACT

In the process of studying the growth of hail and other precipitation forms within wind fields derived from Doppler radar analyses, we have developed GROW, a particle growth model. Forms of ice precipitation are diverse, and the schemes for the detailed growth calculations are lengthy and complex. The attempt has been to be as complete and up-to-date as possible with regard to ice growth processes by accretion and diffusion, with special attention to the complex temperature dependencies and the difficult specification of density, terminal velocity, melting and shedding, and collection efficiency. Less elaborate treatments of aggregation and liquid coalescence are included.

The growth model is combined with either a one-dimensional dynamic and thermodynamic model, with conventional lateral entrainment ("1D"), or a three-dimensional wind field, as may be obtained from a Doppler radar field study or a dynamical model ("3D").

These models are modular, they are easily customized by individual investigators, and they may be run remotely on the NCAR computer system. This Technical Note is intended to guide potential users in using them.
Part I. INTRODUCTION

The purpose of this note is to introduce the user to a particle-growth model and its two associated methods of detailing air motions and thermodynamical conditions within a convective storm environment. These are the one-dimensional and the three-dimensional particle trajectory programs, known as "1D" and "3D." The input data stream is described and examples are given to enable a user to run the computer programs. Representative output plots and printed listings are presented.

The main set of routines is collectively known as the ice-particle growth model (GROW). GROW computes ice particle growth through accretion, diffusion, aggregation, ice particle melting, and evaporation. Water drop growth can also be calculated. The same growth routines are called by both 1D and 3D.

The 1D program is the easiest way to access GROW. It computes modified adiabatic conditions of temperature, liquid water content, and vertical velocity from an environmental sounding at a series heights; height is the only spatial variable. Particles may also be grown in constant conditions, in which case a sounding is not used.

The three-dimensional program is a more elaborate way to access GROW. It uses wind fields at (x, y, z) grid points, as well as a sounding, to describe the environment, thus enabling the user to trace the three-dimensional path of a growing particle, or group of particles, through an entire storm. This model may also be used without GROW for tracing movement of air parcels, or particles with constant fall velocity.
The user may wish to make modifications to any of these programs or specific algorithms, as well as input or output. To facilitate this, descriptions of each subroutine are included in Appendix C. Complete listings and simplified flowcharts of all three programs are also available upon request. When modifications are made or new versions of these programs are implemented, they will be documented as addenda to this technical note. Any problems the user may experience with the programs should be reported, so that they may be corrected. Suggestions for improvements are also welcome, and will be taken into consideration for later versions.

Part II. OVERVIEW OF THE GROWTH MODEL -- PHYSICS

A. Introduction

GROW deals with the growth of the following initial particle types, or habits, illustrated in Fig. 1 (column S-O):

1 = planar crystals (rimed or unrimed),
3 = aggregates (rimed or unrimed),
4 = graupel and hail,
6 = water drops,
7 = frozen drops, or smooth hail,
8 = columns or needles, and
9 = bullet rosettes (spatial crystals).

Habit 2, aggregates that are two-dimensional ("planar" aggregates), and habit 5, graupel that are initially of density between graupel and frozen drops ("smooth" graupel), are not currently in use.
The model physics used in GROW is discussed for the most part in Heymsfield (1982), Heymsfield and Pflaum (1985), and Rasmussen and Heymsfield (1985A,B). The model considers the development of particles of the above types through vapor diffusion (growth or evaporation) and cloud droplet accretion. Growth through aggregation is also considered, although in a very simplified form. The program treats drops through continuous collection, although it is directed primarily toward ice particle growth.

B. Initialization of Particle Mass and Terminal Velocity

The approach given in Heymsfield (1982) is used to prescribe the particle mass at the start of the calculations. For planar, needle, and columnar ice crystals, the crystal axial ratio data and densities are derived according to air temperature based upon the laboratory experiments of Ryan et al. (1976). These data, given in Table 1, are used to derive the crystal mass, assuming these particles are hexagonal. The initial mass of aggregates is taken from Passarelli and Srivastava (1979), and the one for graupel particles is an adaptation of the results in Heymsfield (1978) (see Table 1). Frozen drops are considered initially to be solid ice. Bullet rosette mass is derived assuming the particle contains four identical columnar crystals, each of length equal to half the rosette diameter. The equation is given in Table 1, where the axial ratio and density used are from the data for temperatures less than -21°C.
TABLE 1
Data Used in Initial Mass Computation

<table>
<thead>
<tr>
<th>Air Temperature (°C)</th>
<th>&gt; -3</th>
<th>-3</th>
<th>-4</th>
<th>-5</th>
<th>-6</th>
<th>-7</th>
<th>-8</th>
<th>-9</th>
<th>-10</th>
<th>-11</th>
<th>-12</th>
<th>-13</th>
<th>-14</th>
<th>-15</th>
<th>-16</th>
<th>-17</th>
<th>-18</th>
<th>-19</th>
<th>-20</th>
<th>-21</th>
<th>&lt; -21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Ratio, AR = D/t</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.75</td>
<td>1.20</td>
<td>0.32</td>
<td>0.16</td>
<td>0.12</td>
<td>0.24</td>
<td>0.43</td>
<td>0.75</td>
<td>1.24</td>
<td>1.70</td>
<td>3.85</td>
<td>10.71</td>
<td>20.83</td>
<td>52.00</td>
<td>44.33</td>
<td>30.33</td>
<td>18.75</td>
<td>10.67</td>
<td>6.50</td>
<td>4.30</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>Density, ρ₁ (g cm⁻³)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.85</td>
<td>0.85</td>
<td>0.74</td>
<td>0.50</td>
<td>0.53</td>
<td>0.65</td>
<td>0.74</td>
<td>0.77</td>
<td>0.74</td>
<td>0.67</td>
<td>0.70</td>
<td>0.72</td>
<td>0.62</td>
<td>0.50</td>
<td>0.50</td>
<td>0.53</td>
<td>0.57</td>
<td>0.62</td>
<td>0.66</td>
<td>0.70</td>
<td>0.70</td>
<td></td>
</tr>
</tbody>
</table>

For planar crystals, \( m = (0.65D^3/AR) \rho₁ \) calculated according to temperature, data given above.

For needle and columnar crystals, \( m = 0.65D^3 (AR)^2 \rho₁ \) calculated according to temperature, data given above.

For aggregates, \( m = 7.94 \times 10^{-3} D^{2.4} \), for \( D > 0.136 \) cm,

and \( m = 2.93 \times 10^{-3} D^{1.9} \), for \( D \leq 0.136 \) cm.

For graupel, \( m = 0.1309D^3 + 0.0911D^4 \), for \( D \geq 0.1 \) cm,

and \( m = 0.0621D^3 \), for \( D < 0.1 \) cm.

For bullet rosettes, \( m = 0.65D^3 (AR)^2/2 \rho₁ \) calculated for temperature < -21, data given above.

AR = 0.31

Details of the implementation of the equations for initial mass is given in SUBROUTINE INITS.
The particle terminal velocity is calculated according to a Best number (X) to Reynolds number (Re) approach, whereby empirical relationships are formulated between X and Re for each of the particle types. For graupel and hail with Reynolds numbers above 28, we use an X-Re relationship derived from the drag coefficient data of Knight and Heymsfield (1983). For Re < 28, we use the X-Re relationship for smooth spheres in Beard (1976), and we use an X-Re relationship based on a drag coefficient of 0.6 for Re > 2.4 \times 10^4 (Rasmussen and Heymsfield, 1985A). The equations are shown in Table 2. For frozen drops, we employ the approach given in Heymsfield and Pflaum (1985). In this approach, the X-Re relationship changes from that of a water drop to that of a graupel shortly after drop freezing (see Table 2). The X-Re relationship of Beard (1976) is used for water drops and solid spheres (Table 2). Planar crystal, needle, columnar crystal, and bullet rosette terminal velocities are derived according to Heymsfield (1972) (see Table 2). Terminal velocities of aggregate crystals are derived according to the X-Re relationship of solid spheres.

C. Particle Growth

The heat balance and mass growth rate equations for ice particles are used in their general form to solve both for the particle temperature and mass. The total mass growth rate (\( \frac{dm}{dt} \)) is the sum of the growth rate through accretion (\( \frac{dm_a}{dt} \)) and the growth rate through diffusion (\( \frac{dm_d}{dt} \)).
The Best number, the Reynolds number, for graupel, solid sphere curves (used for aggregates).

<table>
<thead>
<tr>
<th>Equation Used in Terminal Velocity Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X = 2m \rho v^2 g / (p_F v^2 A)$</td>
</tr>
</tbody>
</table>

The Reynolds number, for columns and bullet rosettes, $d'$ replaces $D$.

For graupel,

| $\text{Re} = V_D / \nu$ | $\text{Re} = 0.4874 \times 10^{0.5536}$, for $X > 1.75 \times 10^3$, ($\text{Re} \geq 28$); | $\text{Re} = 10 \left( -1.81391 + 1.34671 \text{AIOX} - 0.006344 \text{AIOX}^3 \right)$, (for $\text{Re} < 28$). |

For frozen drops growing into graupel

| $\text{Re} / \text{Re}_\infty = \alpha - B \ln X / X_0$, where | $\alpha = 1.0$ and $B = 0.057 + 1.26 \times 10^{-5} X_0$. | (A restriction is placed such that $\text{Re} / \text{Re}_\infty \geq 0.7$.) $\text{Re}_\infty$ is derived from the solid sphere $\text{Re}$ given above. $X_0$, the initial Best number, is obtained at the time of drop freezing. |

For planar crystals

| $\text{Re} = 10 \left( -1.17598 + 0.84878 \text{AIOX} - 0.00248 \text{AIOX}^2 - 0.00998 \text{AIOX}^3 \right)$, for $5 < X < 2.2 \times 10^4$. | $\text{Re} = 0.5 \text{AIOX}^{0.558}$, for $X \geq 2.2 \times 10^4$. | (For $X < 5$, a parameterization is used to account for the dependence of $\text{Re}$ on the crystal width; this parameterization appears in subroutine XRHE.) |

For columns and bullet rosettes

| $\text{Re} = 10 \left( -1.10114 + 1.05687 \text{AIOX} - 0.09224 \text{AIOX}^2 + 0.00535 \text{AIOX}^3 \right)$. | (A parameterization is used to account for the crystal axial ratio, see subroutine XRHE.) |

For water drops

| when $D < 0.1 \text{ cm}$, the equation given for solid spheres for mass < 0.004 g is used. | when $D \geq 0.1 \text{ cm}$, a fairly intricate equation from Beard (1976) is used. |

Details of the implementation of the equations in this table are given in subroutine XRHE.
\[
\frac{dm_a}{dt} = A V T \sum_{i=1}^{N} E(D, d_i) LWC(d_i)
\]  \hspace{1cm} (1)

and

\[
\frac{dm_d}{dt} = 4 \pi CD_w F[p_w(T) - \rho_i(T_H)].
\]  \hspace{1cm} (2)

The symbols are defined in Table 3.

Values used for C in Eq. (2) are those given in Pruppacher and Klett (1978) for the particle types considered, and D_w is taken from Hall and Pruppacher (1976). T_H in Eq. (2) is found through an iterative solution to the heat balance equation of the particle using the equation developed in Heymsfield (1982) (Table 4); \rho_i(T_H) is then found from the expressions given in the Smithsonian Meteorological Tables (List, 1947). Expressions for the ventilation coefficient are taken from Hall and Pruppacher (1976), and for spherical particles from Pruppacher and Klett (1978) and Clift et al. (1978). These are given in Table 5.

D. Collection Efficiency

The efficiency at which cloud droplets collide with an ice particle is calculated for graupel particles, frozen drops, and planar crystals in a manner similar to that described by Hall (1980). Detailed equations appear in Table 6. In this technique, the efficiency depends upon the particle's
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Particle crystal cross-sectional area normal to the airflow</td>
</tr>
<tr>
<td>AR</td>
<td>Axial ratio</td>
</tr>
<tr>
<td>C</td>
<td>Particle shape factor</td>
</tr>
<tr>
<td>C_i</td>
<td>Specific heat of ice</td>
</tr>
<tr>
<td>C_p</td>
<td>Specific heat capacity of air at constant temperature</td>
</tr>
<tr>
<td>C_w</td>
<td>Specific heat of water</td>
</tr>
<tr>
<td>D</td>
<td>Ice particle diameter</td>
</tr>
<tr>
<td>DIAM</td>
<td>Diameter of the updraft core</td>
</tr>
<tr>
<td>D_w</td>
<td>Diffusivity of water vapor in air</td>
</tr>
<tr>
<td>E(D,D_i)</td>
<td>Collection efficiency of a droplet of diameter d_i</td>
</tr>
<tr>
<td>F</td>
<td>Ventilation coefficient</td>
</tr>
<tr>
<td>F_x</td>
<td>Parameter used in calculation of the Reynolds number</td>
</tr>
<tr>
<td>K</td>
<td>Thermal conductivity of air</td>
</tr>
<tr>
<td>L_r</td>
<td>Latent heat of fusion</td>
</tr>
<tr>
<td>L_s</td>
<td>Latent heat of sublimation</td>
</tr>
<tr>
<td>L_v</td>
<td>Latent heat of vaporization</td>
</tr>
<tr>
<td>LWC</td>
<td>Total liquid water content</td>
</tr>
<tr>
<td>LWC(d_i)</td>
<td>The liquid water content in droplets of diameter d_i</td>
</tr>
<tr>
<td>M</td>
<td>Mass of a saturated air parcel</td>
</tr>
<tr>
<td>N_i</td>
<td>Concentration of cloud droplets of diameter d_i</td>
</tr>
<tr>
<td>N_r</td>
<td>Total cloud droplet concentration</td>
</tr>
<tr>
<td>R_d</td>
<td>Specific gas constant for dry air</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>Re_s</td>
<td>Reynolds number for solid spheres</td>
</tr>
<tr>
<td>T</td>
<td>Air temperature</td>
</tr>
<tr>
<td>T'</td>
<td>Temperature in the environment</td>
</tr>
<tr>
<td>T_H</td>
<td>Particle temperature</td>
</tr>
<tr>
<td>T_v</td>
<td>Virtual temperature</td>
</tr>
<tr>
<td>V_DROP</td>
<td>Droplet terminal velocity</td>
</tr>
<tr>
<td>V_D</td>
<td>Droplet impact velocity</td>
</tr>
<tr>
<td>V_T</td>
<td>Terminal velocity</td>
</tr>
<tr>
<td>W</td>
<td>Vertical velocity</td>
</tr>
<tr>
<td>W'</td>
<td>Environmental mixing ratio</td>
</tr>
<tr>
<td>W_max</td>
<td>Maximum vertical velocity at an altitude</td>
</tr>
<tr>
<td>W_e</td>
<td>Saturation mixing ratio</td>
</tr>
<tr>
<td>X</td>
<td>Best number</td>
</tr>
<tr>
<td>X_env</td>
<td>Environmental mixing ratio</td>
</tr>
<tr>
<td>X_o</td>
<td>Value of the Best number of a frozen drop at time of freezing</td>
</tr>
<tr>
<td>X_w</td>
<td>Water vapor mixing ratio</td>
</tr>
<tr>
<td>Z</td>
<td>Altitude</td>
</tr>
<tr>
<td>d'</td>
<td>For columnar crystals, distance across the crystal face</td>
</tr>
<tr>
<td>d_i</td>
<td>Median volume cloud droplet diameter</td>
</tr>
<tr>
<td>d_i</td>
<td>Diameter of droplet i</td>
</tr>
<tr>
<td>g</td>
<td>Gravitational acceleration</td>
</tr>
<tr>
<td>m</td>
<td>Mass</td>
</tr>
</tbody>
</table>
TABLE 3 (continued)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{dm}{dt}$</td>
<td>Total mass growth rate</td>
</tr>
<tr>
<td>$\frac{dm_a}{dt}$</td>
<td>Accretional growth rate</td>
</tr>
<tr>
<td>$\frac{dm_d}{dt}$</td>
<td>Diffusional growth rate</td>
</tr>
<tr>
<td>$\bar{r}$</td>
<td>Median volume radius of cloud droplet distribution</td>
</tr>
<tr>
<td>$t$</td>
<td>Time</td>
</tr>
<tr>
<td>$t'$</td>
<td>Crystal thickness (planar crystals) or crystal length (columnar crystals)</td>
</tr>
<tr>
<td>$\Delta Q$</td>
<td>Change in the liquid water mixing ratio</td>
</tr>
<tr>
<td>$\Delta X_w$</td>
<td>Change in specific humidity</td>
</tr>
<tr>
<td>$c$</td>
<td>Ratio of the molecular weights of water and dry air</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Entrainment coefficient</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Kinematic viscosity</td>
</tr>
<tr>
<td>$\rho_a$</td>
<td>Accretional density</td>
</tr>
<tr>
<td>$\rho_F$</td>
<td>Air density</td>
</tr>
<tr>
<td>$\rho_i(T_H)$</td>
<td>Crystal density</td>
</tr>
<tr>
<td>$\rho_i(T_H)$</td>
<td>The saturation vapor density with respect to ice at the particle's temperature</td>
</tr>
<tr>
<td>$\rho_w(T)$</td>
<td>Vapor density of the environment with respect to water saturation at the air temperature</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Dispersion of droplet spectrum</td>
</tr>
</tbody>
</table>

TABLE 4

Equations Used to Iteratively Solve the Particle Temperature

For dry growth (particle temperature < 0°C)

$$T_H = \left[ T \left( \frac{dm_a}{dt} + \frac{dm_d}{dt} \right) - \frac{dm_a}{dt} \right] \left[ \frac{dm_d}{dt} \right] \left( \frac{dm_d}{dt} \right) \left( \frac{dm_d}{dt} \right)$$

The implementation of these equations is given in SUBROUTINE PTEMP. An explanation and justification for these is given in Heymsfield (1982).

For wet growth and melting (particle temperature = 0°C)

The equations used to solve for the fraction of liquid water frozen in wet growth ($T_H = 0°C$ and $T < 0°C$) and the mass melted during the melting of a particle are intricate and thus the user is referred to SUBROUTINE PTEMP1 to see the details. Rasmussen and Heymsfield (1985B) discuss the equations when $T_H = 0°C$. 
TABLE 5
Equations Used to Calculate the Ventilation Coefficient

**Dendrites, Columns, and Bullet Rosettes**

\[ F = 1.0 + 0.104 \text{Re}_L, \] for \( 0.86 \text{Re}_L^{0.5} < 1.0, \)

and \( F = 0.86 + 0.24 \text{Re}_L^{0.5}, \) for \( 0.86 \text{Re}_L^{0.5} \geq 1.0. \)

**Aggregates**

\[ F = (1.0 + (\pi D \times 0.0477 \times \text{Re}_L^{0.5}/C)) \times 1.25. \]

The factor of 1.25 in the equation comes from measurements of the enhancement of the ventilation factor for aggregates over that of spheres of the same Reynolds number and diameter.

**Graupel**

\[ F = 1.0 + \pi D \times 0.0477 \times \text{Re}_L^{0.5}/C, \] for \( \text{Re} < 100; \)

\[ F = 1.25 \times (0.5 + 0.3385 \text{Re}_L^{0.47}), \] for \( 100 \leq \text{Re} < 4000, \)

and \( F = 0.34 \times \text{Re}_L^{0.5} \) for \( \text{Re} \geq 4000. \)

In the second equation, the factor of 1.25 tries to take into account the nonspheriality (oblateness or conical shape) of a graupel particle.

**Water Drops**

\[ F = 0.78 + 0.277 \text{Re}_L^{0.5}. \]

**Frozen Drops**

\[ F = 0.78 + 0.277 \text{Re}_L^{0.5}, \] for \( \text{Re} < 100, \)

\[ F = 0.5 + 0.3385 \text{Re}_L^{0.47}, \] for \( 100 \leq \text{Re} < 4000, \)

and \[ F = 0.5 + 0.136 \text{Re}_L^{0.58}, \] for \( \text{Re} \geq 4000. \)

**Melting Particles**

Equations for \( F \) for melting particles are fairly intricate, and thus SUBROUTINE VENTC should be consulted for these equations.
TABLE 6
Equations Used for Collection Efficiency Calculations

Planar Crystals
\[ RK = 5.52 \text{ Re}^{-1.12} \text{, for Re} < 5, \]
and \[ RK = 1.53 \text{ Re}^{-0.325} \text{, for Re} \geq 5. \]
\[ AK = \frac{|V_t - V_{\text{drop}}|}{(0.5 \times D \times g)} \]
\[ E(d_i, D) = \sqrt{1 - 2(\log_{10}(AK) - \log_{10}(RK) - 2.23607)^2} \]

Columns, Needles, and Bullet Rosettes
AK is given as above, but the crystal's minor dimension (d') replaces D.
\[ A_1 = 0.912 + 0.0292 \ln (\text{Re} - 0.45) \]
\[ RK = 2.39 + (\text{Re} - 0.45)^{-0.2124} \]
\[ B = \log_{10}(RK) + \frac{1}{\sqrt{A}} \]
\[ AB = 1 - A_1 (\log_{10}(AK) - B)^2 \]
\[ E(d_i, d') = \sqrt{AB}, \text{ for Re} \geq 0.495 \]
\[ E(d_i, d') = 0, \text{ for Re} < 0.495 \text{ or } AB \leq 0 \]

Spherical Particles
A rather detailed set of equations is given in Beard and Grover (1974) and will not be reproduced here. The equations are presented in SUBROUTINE COLEFF.

The implementation and more details of the equations in this table appear in SUBROUTINE COLEFF.
mixed Froude number (which is roughly equal to the Stokes impaction parameter) and the Reynolds number. For aggregates, it is considered that the collection efficiency is the same as that for spheres of the same mixed Froude number. For planar crystals, collection efficiencies of Pitter (1977), as adapted by Hall (1980), are used. For graupel and hail, the collection efficiency data for spheres are used, which Heymsfield and Pflaum (1985) have shown to be applicable to graupel through use of the mixed Froude number approach. For needle crystals and bullet rosettes, the data in Schlamp (1975) have been converted into equations representing collection efficiency in terms of the mixed Froude number.

E. Density of Accreted Rime

The density at which a particle is rimed is calculated according to the formulation given in Heymsfield and Pflaum (1985) based on experimental data from laboratory simulations of graupel growth. The rime density, $p$, is expressed in the following functional form, where $f$ represents a function:

$$
\rho = f\frac{\bar{r} V_o}{T_H}
$$

(3)

where $\bar{r}$ is the median volume cloud droplet radius, and $V_o$ the mean droplet impact velocities on the collector particle. The equations for $\rho$ are given in Table 7. The particle's surface temperature $T_H$ is derived using the heat balance equations for the particle, and the droplet impact velocities are given in Rasmussen and Heymsfield (1985B). A lower limit of $\rho = 0.1 \text{ g cm}^{-3}$ is given to the rime density. In the following discussion,
accreted mass is converted into a volume through use of the density. The density of the diffusional growth is specified according to the stage of growth, values of which will be discussed below.

### TABLE 7

**Accretional Density Parameterization**

\[
\rho = 0.30 - \left( \frac{\bar{r} V_0}{T_H} \right)^{0.44}, \text{ when } T_H \leq -5^\circ C, \text{ and }
\]

\[
\rho = \exp \left( -0.03115 - 1.7030 \left( - \frac{\bar{r} V_0}{T_H} \right) + 0.9116 \left( - \frac{\bar{r} V_0}{T_H} \right)^2 - 0.1224 \left( - \frac{\bar{r} V_0}{T_H} \right)^3 \right),
\]

when \( T_H > -5 \) and \( \left( \frac{\bar{r} V_0}{T_H} \right) \leq -1.6 \).

The accretional density \( \rho \) should be limited to a maximum of 0.91 g cm\(^{-3}\).

The equations used to calculate \( V_0 \) are lengthy, and thus the reader is referred to Rasmussen and Heymsfield (1985A) and SUBROUTINE ADDMASS for further details.
F. Evolution of Ice Particle Forms during Dry Growth

Schematics illustrating the assumed changes in the shapes of the various ice particle types considered are given in Fig. 1. Graupel particles and frozen drops grow as spheres in S-4. The diameter increases according to the density of accreted rime based on the mass of diffusional and accretional ice added. For water drops that have just begun to freeze, the heat balance equations for the drop are used to calculate the time required for the drop to freeze (see Table 4). During this period, the particle's surface temperature is considered to remain at 0°C, and the particle grows through accretion by Eq. (1) using a density of 0.91 g cm$^{-3}$ and evaporates through diffusion by Eq. (2) using the same density.

If the particle begins to evaporate in the absence of liquid water, the bulk density remains constant and the change in diameter is then calculated based on the loss of diffusional mass.

The evolution of planar crystals into a spherical form by riming is modeled in a four-stage process. In the first stage, S-1, rime produced from accreted liquid water fills in the interstices between branches of the planar crystal, and diffusional growth leads to an increase in the particle dimensions. The mass given by Eq. (2) is converted into linear growth in this stage by using the axial ratios and density values from experimental crystal growth studies of Ryan et al. (1976), where the particle temperature is used to prescribe these values. For the case of planar crystals that are already rimed, we assume in the program that the particle is a hexagonal form of the same thickness, with a density of solid ice (in which the spaces between crystal branches are initially filled in); thus,
<table>
<thead>
<tr>
<th>Particle Type</th>
<th>View</th>
<th>S-0 Initial</th>
<th>S-1 Filling in and Growing</th>
<th>S-2 Thickening and Growing</th>
<th>S-3 Becoming Filled-in Sphere</th>
<th>Growing as Sphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graupel Hail</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frozen Drop</td>
<td></td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Planar Crystal</td>
<td>top</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>side</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aggregate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Column</td>
<td>top</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>end</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bullet Rosette</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Diagram indicating the modeled development of different particle types during dry growth. Shapes for S-1 and S-2 are at the end of the stage. N/A indicates the particle does not pass through that stage.
growth in stage S-1 is not considered. In the second growth stage, S-2, the planar crystal develops to an axial ratio of 0.3. It still grows outwardly through diffusion, while the rime leads to thickening of the particle. In S-3, the particle develops from a hexagonal form to a spherical graupel. The particle then grows as a graupel in S-4.

If a planar crystal is evaporating in S-0 to S-2, the particle is assumed to maintain a constant thickness-to-diameter ratio and bulk density. In S-3 and S-4 (h/D > 0.3), evaporation is treated as for a graupel.

The growth of unrimed aggregates into graupel and hail is calculated according to a two-stage process. Riming initially fills in the interstitial spaces between the crystals composing the aggregate and between the branches of the individual crystals. Thus, in the first stage, S-3, riming fills in the unoccupied volume contained within an imaginary spherical shell of diameter D that surrounds the aggregate. The density is given by the accretional density (Table 7). The particle can also grow through aggregation in this stage if a linear growth rate (in centimeters per second) is specified by the user and input into the data stream. In the next stage of growth, S-4, the particle grows as a graupel.

If an aggregate is evaporating in stages S-0 or S-3, it is assumed that the bulk density remains constant and the particle decreases its diameter in a spherically symmetrical form.

Columnar crystal growth is treated in three stages. Rime is deposited on the crystal faces in a hexagonal fashion in stage S-2. The volume of the rime added to the particle in a given time step is derived from the accretional mass added (Eq. 1) and the rime density. In this stage the
particle also grows in dimensions according to the diffusional mass added (Eq. 2), where the apportionment of length-to-thickness growth is based on Ryan et al. (1976). When the particle has a length-to-thickness ratio of about < 2, it begins stage S-3 where both the diffusional and accretional mass are used to fill the particle into a spherical shape. The particle grows in this stage in an ellipsoidal shape until its volume is equivalent to that of a sphere of diameter equal to its maximum dimension, whereupon it grows as a graupel in stage S-4. Evaporation is treated as for planar crystals.

Bullet rosettes are considered to be composed of four spatially oriented identical columnar crystals that are joined at one end at the particle center. The interior particle volume in S-2 grows in the same way as for individual columns. When the length-to-thickness ratio becomes < 3:1, the particle is treated as an aggregate in S-3, filling in the internal particle volume to become a sphere.

G. Specification of Parameters during Transitions between Habits

The transitions between particle types are an important part of the model. As the particle form changes, its habit also changes. When a set of conditions describing a particular habit, e.g., a completely filled-in ice sphere, is satisfied, then we say that the particle is that habit (in this case, graupel or habit 4). Table 8 defines each habit. When the particle does not satisfy any set of conditions, then we say it is in transition between habits. In the above discussion, S-3 is always the transition stage, transforming from a hexagonal or spatial form to a spherical form. S-4 may also contain a transitional phase, for example, from
spongy graupel to a solid sphere (habit 4 to 7).

Some parameters are calculated differently depending upon the habit of the particle. When the habit changes, to avoid any abrupt jumps in these values, we make a gradual transition from one habit to the next. Parameters handled in this manner include those calculated as a function of the habit. These are Reynolds number (RE), terminal velocity (VT), area (AREA), shape factor (SHAPE), ventilation coefficient (VENT), and collection efficiency (COLEFF, done separately for each of 15 cloud droplet size categories).

### TABLE 8
Conditions Defining the Habits

<table>
<thead>
<tr>
<th>Habit</th>
<th>Shape</th>
<th>Usual Axis Ratio*</th>
<th>Filled In?</th>
<th>Liquid Water Present?</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. dendrite</td>
<td>hexagonal</td>
<td>&lt; 0.3</td>
<td>yes or no</td>
<td>no</td>
<td>&lt; 0.8</td>
</tr>
<tr>
<td></td>
<td>t' &lt; D</td>
<td></td>
<td>(if yes, then called &quot;rime&quot;)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. aggregate</td>
<td>spherical</td>
<td>1</td>
<td>no</td>
<td>no</td>
<td>&gt; 0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(generally ice &lt; 25% of total volume)*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. graupel</td>
<td>spherical</td>
<td>1</td>
<td>yes</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>6. drop</td>
<td>spherical</td>
<td>1</td>
<td>yes</td>
<td>yes, 100%</td>
<td>1.0</td>
</tr>
<tr>
<td>7. frozen drop</td>
<td>spherical</td>
<td>1</td>
<td>yes</td>
<td>maybe</td>
<td></td>
</tr>
<tr>
<td>8. needle, column</td>
<td>hexagonal</td>
<td>t' = D, D &gt; d'</td>
<td>yes</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 0.33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. bullet rosette</td>
<td>hexagonal</td>
<td>t' = D, D &gt; d'</td>
<td>yes</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 0.47</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*The transition usually starts when the particle reaches the indicated axis ratio or ice volume. However, since the transition cannot begin unless accretional growth is occurring, these numbers are not absolute.
Figure 2 explains the iterative method used to calculate the parameters during the transition stage, shown for a dendrite. When the dendrite enters the transition stage (S-3), particle characteristics at the end of its transition are estimated as closely as possible. The diameter at the end of this stage will be the dimension \((D^2 + t'^2)^{0.5}\) for planar crystals and \((D^2 + d'^2)^{0.5}\) for needles, columns, and bullet rosettes. (The diameter of a spherically shaped particle, such as an aggregate or graupel, is assumed to remain constant to the end of the transition stage.) For the purpose of estimating the mass at the end of the transition, rime density given by the current timestep is assumed to remain constant during the transition. Associated values of the parameters at the estimated end of the transition are then calculated, and a straight-line function is derived between the current values and estimated end-point values. At the following timestep, the derived function is used to calculate the new value of the parameter. The end-point estimate is recalculated at the end of each timestep, in case the diameter or accreted density has changed, and a new transition line function is calculated using the current value and new end-point estimates. The transition is complete when criteria for the new habit are met. Figure 3 gives an example of computed parameters for an unrimed dendrite undergoing various stages of development to a graupel. Plots are shown for all values that undergo transition, except that we show the collection efficiency for only one of our 15 droplet sizes.
Fig. 2. At step \( n \), a value \( n_E \) is estimated for the Reynolds number at the end of the transition, and a straight line function is calculated between it and the current value, \( n_B \). For timestep \( n+1 \), the new value is on the line \( n_Bn_E \). The process is repeated at each step until the new habit criteria are satisfied.
Fig. 3a and b. Values of several parameters (a, area; b, shape factor; c, Reynolds number; d, terminal velocity; e, ventilation coefficient; f, collection efficiency in channel 4) that undergo transitions during the development of a dendrite into a graupel. The labeled, dotted lines show the actual or hypothetical values of the parameter for habits 1 and 4 at the current particle diameter, indicated at the bottom of the plot. The actual calculated values of the parameters are indicated by the solid lines. The particle stages are also shown.
Some parameters that are calculated as a function of habit use the same sets of equations for more than one habit. For instance, the area calculation uses the same equation for all spherical particles, but different ones for dendrites, needles, and bullet rosettes. Thus, a transition function for AREA is needed for a dendrite transforming to graupel, but not for an aggregate becoming a graupel. In the latter case, such a function is therefore not used.

H. Evolution of Ice Particle Forms during Wet Growth and Melting

This section describes the general features of how wet growth and melting are treated for all of the particles when the particle temperature is calculated to be 0°C.²

We define three different types of growth involving liquid water contained within the particle and/or on its surface. A particle may undergo one or more of these stages during its evolution. First is "wet growth" where a particle accumulates liquid water. This occurs where the air temperature is < 0°C, and the particle temperature is > 0°C. The water first fills up any available space within the ice volume. Then it begins accumulating liquid water on its surface. The program uses a parameterization developed in Rasmussen and Heymsfield (1985A) to specify the mass of liquid water that can be contained on the particle surface based on the Reynolds number. Any water that cannot be held on the particle surface is shed.

²For the calculations, we actually used -0.01°C.
Another type is "melting," which can occur when the air temperature is > 0°C. As the particle melts, the volume of water melted is treated in the same manner as the accumulated water described above.

The last type is "residual freezing," which occurs when the particle temperature becomes < 0°C and the particle has accumulated liquid water. Any such water on the surface of the particle is frozen before the internal water. In both cases the water is frozen with a density of 0.91 g cm\(^{-3}\).

The physics used to determine the shapes, temperatures, and terminal velocities of graupel and hail undergoing wet growth and melting is described by Rasmussen and Heymsfield (1985A), and the calculations are done in SUBROUTINE PTEMP1. The equations used to calculate growth in this stage will not be presented here because of their length. Briefly, one of four heat transfer equations can be used to calculate the particle temperature; the specific equation used depends upon the stage of melting. For example, one choice is used when the particle is small enough to contain a liquid water layer on its surface. The heat transfer equations are then used to calculate the change in the diameter of the ice core as a function of time. Terminal velocities for particles which have already begun to shed liquid water are calculated using the laboratory finding that the Reynolds number of such particles is a linear function of the mass remaining.

Terminal velocities during the transition from a "dry" graupel or hailstone to one that just becomes wet are derived as follows. For Reynolds numbers greater than 4,000, the drag coefficient is specified to be the same as those for a dry hailstone. For lower Reynolds numbers, the
drag coefficient of the dry hailstone or graupel is slowly changed to that of a smooth water-coated sphere, according to the mass of liquid water contained on the particle's surface. When low density graupel are melting or are growing wet, all residual liquid water is allowed to soak into the particle's interior. When the particle's interior volume is completely filled in, terminal velocities are then calculated as discussed previously for graupel and hail. Laboratory experimental results are used to estimate the mass of liquid water that the particle surface can contain. When this critical mass is exceeded, it is shed from the particle. Two parameterizations are used to estimate the density of rime accreted on a particle during wet growth at temperatures below freezing. In one, assuming high density growth, all frozen water is assumed to have a density of 0.91 g cm\(^{-3}\). In the second, spongy wet growth, an ice matrix with a density of about 0.3 g m\(^{-3}\) is assumed to retain some of the accreted liquid water in the interstices of the particle. The density for the spongy ice matrix is specified according to laboratory measurements, and unfrozen water is soaked into the ice matrix. Any excess water is allowed to accumulate in a bulge near the particle's equator.

The physics used to model the development of the other particle forms during wet growth and melting is given by Heymsfield (1982). Briefly, any unfrozen liquid water is soaked into a particle, and eventually the particle melts into a spherical form, whereupon it is treated as a drop. Particle temperatures and the fraction of frozen mass are calculated in SUBROUTINE PTEMP1.
Part III. OVERVIEW OF THE GROWTH TRAJECTORY PROGRAMS

A. One-Dimensional Model

If the particles are to move vertically, an environmental sounding must be input. The values used are pressure, temperature, and environmental water vapor mixing ratio as a function of altitude. The program then calculates two vertical profiles of vertical velocity and liquid water content, from a one-dimensional parcel model. One set of profiles is based on unmixed ascent, while the other uses a parcel model incorporating entrainment of drier environmental air. The equation used to calculate these profiles is given in Table 9. All vertical profiles so obtained can be listed, and ascent with entrainment can be compared with unmixed ascent. The entrainment coefficient which is adjusted by the user to obtain the desired cloud top height must be specified in the data input stream, as discussed later. The mixed-ascent set of profiles is the only one used for the calculations in 1D.

All that is required for particle initialization is a beginning habit, size, and desired initial temperature. The program searches the in-cloud profile for the altitude of that temperature and determines other parameters at that point. The particle is vertically advected to new altitudes at subsequent timesteps, using air motion interpolated between adjacent levels on either side of its current position and particle terminal velocity from GROW. The in-cloud temperature and liquid water content are calculated by interpolating between known values at points on either side of the particle position.
It is also possible to specify that constant liquid water content and/or vertical velocity values will be used. The particle is allowed to move within the cloud subject to these constant conditions, while values for the other parameters are taken from the profile.

**TABLE 9**

**Equations for Calculating Temperature, Liquid Water Content, and Vertical Velocity Profiles**

\[
-\frac{dT}{dZ} = \left[\frac{g}{C_p} \left(1 + \frac{L_v W_s}{R_d T}\right) + \frac{1}{M} \frac{dM}{dZ} \left(\frac{L_v}{C_p} (W_s - W')\right)\right] \sqrt{1 + \left(\frac{C_p R_d T^2}{\epsilon L_v W_s}\right)}
\]

The temperature is calculated by numerically integrating the above equation, using the initial cloud base conditions specified by the user. The term \(\frac{1}{M} \frac{dM}{dZ} = 2 \mu \frac{\mu}{\text{DIAM}}\). The entrainment coefficient \(\mu\) is specified by the user.

The liquid water content is calculated by a numerical integration of the equation:

\[
\Delta Q = \Delta X_w - 2 \mu \Delta Z \left(\frac{X_w (T) - X_{env}}{\text{DIAM}}\right),
\]

\[
\text{LWC} = \rho_F \Sigma \Delta Q
\]

where \(\Delta Q\) is the change in the water mixing ratio between two altitudes (10-m separation), \(\Sigma \Delta Q\) is the total water mixing ratio, \(\Delta X_w\) is the change in the specific humidity between the two levels, and \(\Delta Z\) is the 10-m altitude increment used in the integration.

The change in the vertical velocity of the parcel is

\[
\frac{d(W^2/2)}{dZ} = g \Delta T_v/T_v - \Sigma \Delta Q - \mu W^2/\text{DIAM},
\]

where \(\Delta T_v\) is the difference in the virtual temperature of the air and environment.
If constant particle growth conditions are desired, then the appropriate temperature, pressure, and liquid water content are specified by the user. Alternatively, default values may be used (given in Appendix A).

A log normal cloud droplet size distribution is specified, given input of the total droplet concentration and dispersion value. Droplet concentrations in each of 15 equally spaced 3-μm diameter bins are then calculated and used by the program (Table 10).

The length of timestep and maximum time of particle growth are specified in the data stream. Each particle runs to the time limit unless it goes outside of the sounding range or outside the liquid water region (if moving), or if the diameter becomes 0.

B. Three-Dimensional Model

A unique factor of 3D is the use of wind field data, which enables the movement of growing particles in a three-dimensional cloud. Customarily, winds obtained from multiple-Doppler radar syntheses have been used, but the user could use other sources as long as these data are in the proper format. The data format currently in use is the CEDRIC format (Mohr et al., 1985). The program fetches fields for U, V, W, and reflectivity at each level of the cloud. For each X, Y, Z position the values are scaled and stored in one word that is later retrieved and unscaled when needed.

The user may choose to input several radar volumes and specify the length of time to use each one. The program will jump to the next volume after the particle has grown for the desired number of minutes using the current volume.
TABLE 10

Specification of Droplet Size Distribution and the Liquid Water Content

Drop Size Distribution

The drop size distribution in 1D and 3D is calculated from

\[ N_i = N_o \exp \left[ - \frac{(d_i - \overline{d})^2}{2 \sigma^2 \bar{d}^2} \right], \]

where \( N_i \) is the concentration of droplets of diameter \( d_i \), \( N_o \) a proportionality constant given by

\[ N_o = N_T \sqrt{2}/(\pi \sigma \bar{d}), \]

\( \bar{d} \) the median volume cloud droplet diameter given by

\[ \bar{d} = [LWC/((\pi/6) N_T)]^{1/3}, \]

and \( N_T \) the total droplet concentration.

The dispersion of the droplet spectrum, \( \sigma^2 \) (default = 0.25), and \( N_T \) may be input into the program. If \( N_T \) is not specified, then the equation \( N_T = 475 \ LWC^{0.5} \), is used. The drop size distribution \( N_i \) is adjusted so as to obtain the specified liquid water content.

Liquid Water Content

The following relationship expresses the fraction of the adiabatic liquid water content (\( f \)) at a location to the ratio of the vertical velocity (\( W \)) to the peak vertical velocity at that altitude (\( W_{\text{max}} \)) in 3D:

\[ f = f_{\text{max}} \left(1.5 \frac{W}{W_{\text{max}}}\right)^{0.5} \]

0. \( \leq f \leq f_{\text{max}} \)

This means that \( f = f_{\text{max}} \) whenever \( W \geq 0.67 \ W_{\text{max}} \). The value for \( f_{\text{max}} \) may be input into the program (default = 1.).
Particles are initialized in an array of positions. As a particle moves along its path, the next position is calculated from the particle terminal velocity (from GROW); the U, V, and W winds at the current point; the storm's horizontal movement U and V; and the given timestep length. The U, V, and W at the particle position are calculated by interpolating winds from the eight surrounding grid points.

An environmental sounding is needed (for estimating the growth temperature, among others). The program uses pressure, temperature, the equivalent potential temperature, altitude, water vapor mixing ratio, U, and V. Adiabatic values of temperature and liquid water content are determined from these values and cloud base conditions. Liquid water content is reduced from its adiabatic value as a function of vertical air motion (Table 10). It is further depleted above -25°C as glaciation occurs. Also, the U and V from the sounding may be used for winds when the particle goes outside of the radar field.

The user may initialize particles based on reflectivity and in-cloud air temperature. Instead of starting particles throughout the given field, the program first checks the probability of a particle of specified habit and diameter appearing in a location with that reflectivity and air temperature. If these data indicate that such an initial particle is unlikely to exist in these conditions, no growth trajectory is computed. The current set of probabilities is based on the findings of Heymsfield and Musil (1982) from a storm on 22 July 1976 in northeastern Colorado. However, this approach may be modified to coincide with other data.
The particle growth may end under any of the same conditions as in 1D. It will also terminate at any time it leaves the region where radar data is available, leaves the plot area, or the number of timesteps exceeds the size of the data array (maximum 500 steps).

The 3D model may be used without GROW to trace air parcel movement. A particle of some size should be input to prevent program run-errors, but its terminal velocity is not taken into account in calculating its next position. This may also be done in the reverse direction, to find the beginning locations of an array of air parcels. Because of the complexity of the growth calculations, this option may not be used when particle growth is employed.

Part IV. RUNNING THE PROGRAMS

A. General

As previously mentioned, the program GROW is accessed through either 1D or 3D. The input for both programs follows the same format, and many of the input parameters are the same. The basic input form is an 80-character card image, beginning with a keyword, and usually followed by one or more associated values. The format is usually (A8, 9F8.0).

In some cases, several related values are specified on the same card. For example, in 3D the X range for initialization of particles may be specified as:

```
X 10. 25. 1.
```

where 10. is the first X value to use, 25. is the last X value to use, and 1. is the increment. These must be given in the designated order.
In other cases, an array of values is specified for a single parameter. For example, to specify the diameters to be initialized in a run, the card may look like:

```
DIAM 0.005 0.01 0.02 0.05 0.1 0.2 0.5 1.0 2.0
```

In this way, up to nine values may be specified for the one parameter. It would be treated in the same way as doing several run subsets, changing only the diameter for the next set. Other parameters that may be specified to loop through for several values include habit for both 1D and 3D and initial temperature, liquid water content, and vertical velocity for 1D. The program will loop through the values, initializing a particle for each possible combination. If fewer than the maximum number of values are to be used, the right-most portion of the card is simply left blank.

Most parameters have associated default values. This enables the user to input only the number of cards for the parameters to be altered. After a set of parameters has been specified, the user signals the program that the data set is ready to run by the card:

```
GO
```

When that run subset is complete, the program returns to the input routine for another data set. Only values to be changed for the next run subset need be specified. Thus, if it is desired to initialize 14 diameters for the run, the user could use the card sequence:
When the user is ready to terminate the entire run, the end is signaled by the card:

DONE

Both programs use an environmental sounding. It may be read directly in the data stream or from another unit, or from the CCOPE rawinsonde archive. Information on available CCOPE rawinsonde data may be obtained from the 1981 CCOPE Data Inventory. If read directly, required values are pressure, temperature, and water vapor mixing ratio, as a function of altitude. In addition, 3D needs equivalent potential temperature, $U$, and $V$. Certain cloud base information is also required.

The parameters (keywords) that are common to both programs include: TIME, the timestep length; PRINT, frequency to output descriptive information along the trajectory; HABIT, the habits to initialize; DIAM, the particle diameters to initialize; SOUND, the sounding information; DROP, the drop size distribution information; RH and TPROF, the optional relative humidity and temperature profiles; GO; DONE; and some growth options. A complete list of the input parameters, along with descriptions, units used, and default values for both 1D and 3D is included in
Appendix A.

B. One-Dimensional Model

Parameters of particular interest and specific to 1D are described in this section. It has already been mentioned that the particle can either be allowed to move in the updraft or remain at constant (T, LWC, and pressure) conditions. The cards that specify those are:

MOVE
or
CONST

It is possible to use both within a single run, but whenever MOVE is specified a sounding must be input.

Particles are initialized by specifying the initial air temperature, rather than altitude. If MOVE is specified, the given temperature pertains only to the beginning, whereas CONST keeps the air temperature fixed during all the growth. Again, up to nine different temperatures may be specified in a single dataset. It is also possible to select up to nine constant liquid water contents (LW). If one is not specified, liquid water content is determined from the sounding (if a sounding is given), or a default value is used. If LW is specified, it will be constant even in moving conditions. In the moving case constant vertical velocity (VV) may also be given. If it is not specified, vertical velocity is computed from the sounding information.
A complete description of input parameters is included in Appendix A.

C. Three-Dimensional Model

The primary additional information that must be included in the input for 3D is the wind field data. These are typically from multiple-Doppler radar syntheses, and are read with the package that accesses CEDRIC format data (Mohr et al., 1985) called CARTIO. The radar data are typically on magnetic tapes or mass storage volumes, with one or more radar volumes in a data set. Information on radar data available from the CCOPE field experiment is given in the 1981 CCOPE Data Inventory. Input unit numbers, radar volumes' names, length of time to use individual volumes, and names of the desired U, V, W and reflectivity fields are included in the input card stream. If the storm motion U and V are not to be taken as (0,0), they must be specified.

3D starts particles growing at several X, Y, and Z positions as specified by input cards. If the user desires output plots of trajectory position and information particle size, the plot window size must be listed. The dimensions of the plot are typically larger than those of the starting positions.

Part V. OUTPUT
A. General

Both programs print out a brief description of the run to be done. The 3D program includes the header information from the radar volume(s).

A printout of several trajectory descriptive parameters may be generated from program GROW. The frequency of the printout is specified in
the input stream. However, the user should be aware that this may generate large amounts of printout, particularly with 3D, and this option should be used with caution. Figure 4 gives an example of a printout, including descriptions of the printed values. The form and values to be printed may be tailored to individual needs.

Plots may be generated showing the values of various parameters along the trajectory. These are used primarily for diagnostic purposes and the ones to be plotted must be specified. The potential to generate a great deal of microfilm exists, and so the user should be wary, particularly with 3D, which typically initializes many more points. Refer to Part II, Section G, for a description and Fig. 3 for an example of the parameter plots.

Some generated data may be saved on mass storage or magnetic tape devices for further analysis. Since each researcher's output analysis is likely to take on a different direction, we assume that the format for each case will need to be different. We therefore leave it to the users to devise their own output format where needed.

B. Three-Dimensional Model

The 3D model can generate several different types of output on microfilm. The program loops outermost for initial habit, then diameter, initial X, initial Y, and initial Z. Some of the output types are grouped by initial Y and Z. Others include initial X also. Some show only individual particles.
MODE gives the habit or transitional state of the particle. A single number indicates the habit at which the particle is growing. A "T" with a number indicates the habit toward which the particle is in transition.

1MODE gives the habit or transitional state of the particle. A single number indicates the habit at which the particle is growing. A "T" with a number indicates the habit toward which the particle is in transition.

2ICEO is the wet/dry growth state of the particle: 0 = dry growth; 1 = wet growth; 2 = melting; 3 = residual freezing.
The first output type is a list of the trajectory points (Fig. 5) for each particle, listed as often as the user requests. The left side gives the beginning information for the particle, as well as the end code (reason for termination). If the particle is never initialized (because it was outside the radar field, or inappropriate reflectivity value), or if it does not run a minimum number of timesteps, then this is the only line given. Otherwise, the right side lists the position and size of the particle at the desired frequency. The user could add other parameters to this, if desired.

Fig. 5. Example of microfilm output of trajectory listings.
The particle trajectories may be plotted as projected on several different planes. All of the trajectories that begin on a given line are plotted on the same frame. For instance, the XY projection shows the paths of all particles initialized at the given X and Z values, but for all initial Y values. Separate plots are then done for the different initial X and Z values, as well as different habits and/or diameters. Plots included are X vs Y (by initial Z), X vs Z (by initial Y), Y vs Z (by initial Y), and time vs Z (by initial Y). All are separated by initial habit, diameter, and X position. Figure 6 shows a series of trajectory plots. A symbol, plotted at the frequency requested by input, shows the major size and particle type characteristics.

Figure 7 shows three-dimensional perspective plots of the particle trajectory. On the same frame another plot shows the projections of this trajectory onto each plane. The frame also shows several critical parameters plotted as a function of time. One frame is used for each particle initialized. The input stream also specifies the X, Y, Z position of the eye for the perspective plots, as well as onto which plane to project the lines of the trajectory, and the frequency of that projection.

Time-plots show the positions of all initialized particles at the times of interest. As many as eight times may be specified. XY planes at several levels in the cloud are plotted, and a symbol indicating the particle size and type is plotted for each particle on the plane nearest its position. The ΔZ, used to determine which levels are plotted, is specified in the input. All initial X, Y, and Z positions are included, but different plots are done for each initial habit and diameter. Figure 8 gives
Fig. 6. Examples of trajectory plots of each of the four possible planes: X-Y; X-Z; Y-Z, and time-z.
Note that the axes are scaled so that the distances are all plotted in correct proportion to each other. The symbols plotted give the particle stage of growth, as indicated in the plot heading: *
indicates an unfilled-in particle (such as a dendrite or aggregate, A indicates a filled-in particle (such as a graupel or frozen drop), O shows a wet particle (melting or growing wet), X shows a completely melted drop. There are also four possible sizes for the symbol, each indicating a particular size range, given in the plot heading.
Fig. 7. Example of a perspective plot of a particle trajectory, including plots against time of several parameters.
Fig. 8. Example of time plots showing particle positions after 30 min for several levels in the cloud.
a series of time plots showing the array of particles after 30 minutes of
growth.

Level plots are similar to time plots but show the progression through
time at a particular level of interest. For example, we may be interested
in seeing the fallout at the ground of the given particle type over a
period of time. As many as eight levels may be specified. Plots are done
for the desired level(s) at the time frequency given in the input stream.
A composite plot of all the times and a composite with positions adjusted
for storm movement are also done. Figure 9 shows a series of level plots
at 0.8 km (ground level) done every 5 min.

Another type of summary plot includes initial position and final posi-
tion plots. In these, a number is plotted at either the initial or final
position of the particle, giving the value of the desired parameter: final
values of diameter, X, Y, Z, and reflectivity; maximum values of diameter,
Z, vertical velocity, liquid water content, and reflectivity; total time;
and end code. A separate initial position plot is done for each initial Z
level (as well as habit and diameter). The final position plots include
all initialized particles of a given habit and diameter. A separate
(series of) plot is done for each requested value. The program can also
plot the final positions of particles with a final dimension greater than a
designated size, with a corresponding plot of those particles less than or
equal to that size. An array of as many as eight critical diameters is
input. Any of these plots may be overlaid with a contour plot of any of
the radar fields which are used: reflectivity, vertical velocity, U, and
V. The input stream contains information on the contour intervals desired.
Figure 10 is an example of an initial-position plot showing final diameter and overlay of reflectivity contours, a final-position plot also showing final diameter, and a final-position plot of all particles of final diameter greater than 0.5 cm, overlaid with the reflectivity field contours.

Fig. 9. Example of level plots for 0.8 km, showing that level at a series of times, plus the composite of all the times.
Fig. 10. Example of an initial-position plot, showing final size, overlaid with reflectivity contours; final-position plot of final size; and final position-size plot indicating positions of all particles of diameter greater than 0.5 cm, overlaid with reflectivity contours.
Part VI. TESTS OF THE GROWTH MODEL AND CONCERNS

Our set of test cases for the growth model was submitted through the 1D model and run both with constant conditions and in updrafts. We were primarily interested in checking the paths on the parameter plots, to make certain that the parameters derived during changes from one habit to another were satisfactory. The test set is described in Table 11.

Table 11

SPECIFICATIONS OF GROWTH MODEL TEST SET

All particles were run with constant liquid water contents of 0., 0.5, 1., and 2. g m\(^{-3}\). In addition to constant conditions, they were run with constant vertical velocities of 0.5, 1., and 2. m s\(^{-1}\).

<table>
<thead>
<tr>
<th>Habit</th>
<th>Diameters (cm)</th>
<th>Temperatures (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(constant or initial)</td>
</tr>
<tr>
<td>1 - dendrites</td>
<td>.01 .05 .1 .2</td>
<td>-12 -15 -17</td>
</tr>
<tr>
<td>3 - aggregates</td>
<td>.05 .1 .2 .5</td>
<td>-15</td>
</tr>
<tr>
<td>4 - graupel</td>
<td>.005 .01 .05 .1 1 2.</td>
<td>-5 -15</td>
</tr>
<tr>
<td>6 - drops</td>
<td>.01 .05 .1</td>
<td>-5 -10</td>
</tr>
<tr>
<td>7 - frozen drops</td>
<td>.01 .05 .1</td>
<td>-5 -10</td>
</tr>
<tr>
<td>8 - columns</td>
<td>.005 .01 .05 .1</td>
<td>-3 -5 -7</td>
</tr>
<tr>
<td>9 - bullet rosettes</td>
<td>.005 .01 .05 .1</td>
<td>-25</td>
</tr>
</tbody>
</table>

Some problems with these parameter plots have arisen. When a particle begins a transition to a different habit, the program begins plotting the parameter values at the new habit, as well as continuing to plot those for the previous habit. Any time a parameter value is calculated for a habit
other than that of the current particle, we call it hypothetical. This is our estimate of the characteristics of the particle if it had the current diameter, volume, and mass. In some cases, the trace of a parameter in the transition between habits crosses the trace of one or the other of the two hypothetical habits (see Fig. 3, ventilation coefficient). We have considered making those two traces the boundaries of the transition value. But it is not clear that such a system would not create more error than it would eliminate. It is entirely possible, and sometimes quite clear, that the line in error is that of the hypothetical habit. This is because it is difficult to define the hypothetical particle in terms of the actual particle, since the characteristic shapes can be so different. In general, as long as the transition line makes a nice curve, we are satisfied.

We have used experimental data to define the particle characteristics wherever possible. Where such data do not exist, we have done our best to extrapolate from what we do know. No doubt, more work will be done in this area, and we will continue to update the programs to reflect new findings. Of particular concern are the transitions between particle types where liquid water is involved—transitions to and from habits 6 and 7. We know that wet particles behave differently than dry ones, and that the smooth transition lines found during dry growth are probably not appropriate during wet growth. This is an area of the model which is undergoing the most development.

Columns (as well as bullet rosettes, which are assemblages of columns) are treated as having the same thickness throughout their length (Fig. 1). Some evidence indicates that this is not always the case. For example,
when these particles fall into the planar crystal growth region, the ends can grow outwardly like dendrites, while the main particle maintains its columnar shape (Fig. 11). The model does not deal with this phenomenon; rather, we thicken the particle uniformly throughout its length. We expect to incorporate a more realistic model for this case in the future.

In some temperature regions, columns and dendrites grow at an axial ratio of nearly 1:1. This can cause a problem when the thickness/diameter ratio becomes > 1, since we always say that the diameter is the largest dimension (so the axial ratio must therefore always be less than 1). A column is defined as having its height greater than its dimension across the crystal, while a dendrite is the opposite. So if the axial ratio becomes > 1, we redefine the crystal as changing from a dendrite to a column, or vice versa. This case may be reworked in future program versions.

Fig. 11. Picture of a capped column and a capped bullet rosette.
Acknowledgments

The authors wish to thank Charles Knight and L. Jay Miller for their review of this document, Roy Rasmussen and John Tuttle for their programming and review efforts, Carl Mohr and Ellen Garvey for their programming work, and Frances Huth for typing the manuscript.
Appendix A. Input Descriptions

A. General

The descriptions in this section are common to both 1D and 3D. Each card image begins with a five-letter keyword, followed by one or more values defining the parameter. The format is (A8, 9F8.0), except where otherwise indicated. Some cards contain eight-character alphanumeric fields (A8) in place of some floating-point fields (F8.0). Characters in the alphanumeric fields must be left-justified. Values may be placed anywhere within the numeric fields as long as they contain decimal points. Otherwise they should be right-justified and will be read as integer values. Some parameters are specified as arrays, so that several values (as many as 9) may be defined in one run subset. If fewer than nine values are desired, the right-most portion of the card is left blank. The program will then loop through all the desired values, and initialize one particle for each possible combination of values.

Any card beginning with an "*" is taken by the program to be a comment card. This feature could be used for labeling or for internal documentation of the data stream.

The following is a list and description of the input parameters.

<table>
<thead>
<tr>
<th>Code</th>
<th>Variable Name</th>
<th>Definition</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>*</td>
<td>COMMENT CARD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TIME</td>
<td>TIMSTP</td>
<td>Size in seconds of the timestep</td>
<td>10.</td>
</tr>
<tr>
<td>TMIN</td>
<td>Number of minutes for duration of the model</td>
<td>10. (TMIN used for 1D only)</td>
<td></td>
</tr>
<tr>
<td>PRINT</td>
<td>NPRNT</td>
<td>Print data each NPRNTth timestep, starting</td>
<td>0.</td>
</tr>
</tbody>
</table>
at the first. If 0, then no printout of trajectories.

NPRDD  Write timestep data to microfilm at each NPRDDth step
        (NPRDD used for 3D only)

SOUND IUNIT  Unit number to read environmental sounding
SFLAG  Flag indicating whether sounding is read
        directly or from sounding tape
        1 = Using routine SNREAD, choose desired
        sounding from general sounding tape.
        2 = Read sounding directly. If IUNIT = 5, then
        sounding data will be read in the input
        stream following the 'SOUND' card. Otherwise,
        the sounding will be read from the unit
        specified, in the same format as if it were
        in the input stream.

IDATE  Date of sounding (YYMMDD)  810801.
ITIME  Time of sounding (HHMM)  1630.
LOC  Location where sounding was taken  MILES CITY.

Notes: The format for this card is (A8, 4F8.0, A8).
For sounding cards that are read directly, the format is
(8X, 8F8.0). Parameters read are:
- pressure (MB)
- altitude (meters above sea level)
- environmental temperature (°C)
- water vapor mixing ratio (grams/kg)
- moist adiabatic temperature (°C)  3D only
- equivalent potential temperature (°K)  3D only
- U (meters/sec)  3D only
- V (meters/sec)  3D only
The end is signaled by a blank card (or all 0's).

CLOUD PO  Cloud base pressure (MB)  711.
ZO  Cloud base altitude (meters)  3000.
TO  Cloud base temperature (°C)  12.0
RMXO  Cloud base water vapor mixing ratio  11.2

Note: These refer to the input sounding. Defaults are from
Miles City, 1 August 1981.

DROP SIGSQ  Dispersion of droplet spectrum  0.25
DCONC  Drop concentration (number per CC)  475. √LWC

HABIT HABIT(I)  Array of particle habits to initialize
possible habits:
- 1 unrimed dendrites
- 11 rimed dendrites
- 3 unrimed aggregates
- 13 rimed aggregates
- 4 graupel or hail
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIAMS(I)</td>
<td>Array of particle diameters (cm) to initialize</td>
</tr>
<tr>
<td>AOPT</td>
<td>Linear growth rate for aggregation of aggregates 1.</td>
</tr>
<tr>
<td>ISHED</td>
<td>Flag for which set of shedding calculations to use: 1 = UCLA wind tunnel results 2 = Chong and Chen results</td>
</tr>
<tr>
<td>IMELT</td>
<td>Flag for whether or not to allow melting 1 = allow melting 2 = no melting</td>
</tr>
<tr>
<td>LWFRZ</td>
<td>Temperature (°C) at which to begin linear freezing of liquid water. If 0, then no freezing occurs.</td>
</tr>
<tr>
<td>TFRZ1</td>
<td>Temperature (°C) at which freezing of liquid water is total. If temperature ( \leq \text{TFRZ2} ), LW is 0.</td>
</tr>
<tr>
<td>TFRZ2</td>
<td>Coefficients to define relative humidity by a profile equation of the form ( \text{RH}(Z) = A + B*Z ).</td>
</tr>
<tr>
<td>A1, B1</td>
<td>(none)</td>
</tr>
<tr>
<td>A2, B2</td>
<td>(none)</td>
</tr>
<tr>
<td>ZRH</td>
<td>Altitude (km) defining the boundary between the regions of the 2 different pairs of coefficients. If ZRH = 0, then A1, B1 only are defined. If liquid water exists, then RH = 1, regardless.</td>
</tr>
<tr>
<td>TPROF</td>
<td>Set of parameters to define temperature profile in same manner as for 'RH'.</td>
</tr>
<tr>
<td>A3, B3, A4, B4, ZT</td>
<td>(none)</td>
</tr>
<tr>
<td>PLPRM</td>
<td>Which parameter plots to do. Desired plots are indicated by code names and will be done in the order given. As many as 20 may be done. If more than 9 plots are needed, 1 or 2 additional cards may be included. (The code PLPRM is optional on the subsequent cards if they immediately follow the first.) Acceptable plot codes are:</td>
</tr>
<tr>
<td>KPLT(I)</td>
<td>particle area</td>
</tr>
<tr>
<td></td>
<td>shape factor</td>
</tr>
<tr>
<td></td>
<td>Reynolds number</td>
</tr>
</tbody>
</table>
VT  terminal velocity
VENT ventilation coefficient
CE1, CE2...CE15 collection efficiency in channel 1, channel 2,...channel 15.

Code names should be left-justified within the field. Unrecognized codes will be ignored.

**Note:** The format is (10A8).

**GO** (none) Signals that all needed parameters have been specified and run should begin. Any number of data sets may be run, each ending with the "GO" card. Only indicated parameters are changed from one run to the next.

**DONE** (none) Signals end of all data sets. Program terminates.

### B. 1D

The following parameters are unique to the one-dimensional model.

<table>
<thead>
<tr>
<th>Code</th>
<th>Variable Name</th>
<th>Definition</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROP</td>
<td>(none)</td>
<td>Indicates that the particle will grow at constant temperature, liquid water content, and pressure.</td>
<td>CONST</td>
</tr>
<tr>
<td>MOVE</td>
<td>(none)</td>
<td>Indicates that particle will move in the updraft during growth. A sounding must be input.</td>
<td>CONST</td>
</tr>
<tr>
<td>CLD2</td>
<td>W0</td>
<td>Cloud base vertical velocity (m/sec)</td>
<td>6.</td>
</tr>
<tr>
<td>CORED</td>
<td>Diameter of updraft core (meters)</td>
<td>7000.</td>
<td></td>
</tr>
<tr>
<td>XMU</td>
<td>Entrainment coefficient (adjusted by the user to obtain the correct cloud top height)</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>KPRINT</td>
<td>Flag for printing THERMO array</td>
<td>0.</td>
<td></td>
</tr>
</tbody>
</table>

**Note:** These refer to the input sounding. Defaults are from Miles City, 1 August 1981.

| TEMP | ARFT(I) | Array of temperatures (°C) at which to initialize particles | -5. |
| LW | ALWC(I) | Array of liquid water content (g/m^3) values to use. If specified, then it will be constant. Default used only if no sounding | 1. |
| PRES | PS | Pressure (MB). If specified, it will be constant. Default used only if no sounding | 1000. |
VV  VV(I) Array of vertical velocities (m/sec) to use. (none) If specified, then it will be constant

CLPS  CTIME Number of minutes after which to "collapse the updraft." W and LW become 0. RH and TEMP profile can be specified

C. 3D

The following parameters are unique to the three-dimensional model.

When assigning logical unit numbers for radar and sounding input volumes, note that units 1, 2, 3, and 8 are reserved for use by the program.

<table>
<thead>
<tr>
<th>Code</th>
<th>Variable Name</th>
<th>Definition</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>WIND IU</td>
<td>Unit number to which the wind field data are assigned</td>
<td>10.</td>
<td></td>
</tr>
<tr>
<td>IREW</td>
<td>Flag for whether or not to rewind the tape. (1 = yes or 0 = no). If the tape has not been used for a previous volume, use 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VOLTIM</td>
<td>The time, in minutes, for which to use this volume</td>
<td>10.</td>
<td></td>
</tr>
<tr>
<td>VOLNAM</td>
<td>Volume name</td>
<td>UNKNOWN</td>
<td></td>
</tr>
<tr>
<td>REPNAM</td>
<td>Name for reflectivity field</td>
<td>REF</td>
<td></td>
</tr>
<tr>
<td>UNAM</td>
<td>Name for U field</td>
<td>U</td>
<td></td>
</tr>
<tr>
<td>VNAM</td>
<td>Name for V field</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>WNAM</td>
<td>Name for W field</td>
<td>W</td>
<td></td>
</tr>
</tbody>
</table>

Notes: The program will accept up to 15 wind volumes for a run subset, and these will be used sequentially. If "WIND" is specified in a later subset, then it will replace the wind fields originally given. The format of this card is (A8, 3F8.0, 5A8). The code WIND is optional on subsequent cards if they immediately follow the first.

SMOVE STORMU Storm movement (m/sec) in X direction | 0. |
STORMV Storm movement (m/sec) in Y direction | 0. |
SREL Flag for whether radar data are storm relative (= 1) or ground relative (= 0). If radar data are storm relative, then STORMU and STORMV are still used for adjusting U and V winds of sounding, and/or for calculating actual ground positions for level plots. | 0. |
ZOUT ZOUT Altitude (km above sea level) at which particle is assumed to have fallen out. This is the
lowest altitude at which trajectories are calculated.

WATER FRADIA Fraction of adiabatic liquid water contained in the maximum updraft region (0 ≤ FRADIA ≤ 1.)

XYZ BEG(1) Initial X value to be used for track starts (none)
END(1) Last X value to be used for track starts (none)
RINC(1) Increment for X value starting positions (none)
BEG(2) Initial Y value to be used for track starts (none)
END(2) Last Y value to be used for track starts (none)
RINC(2) Increment for Y value starting positions (none)
BEG(3) Initial Z value to be used for track starts (none)
END(3) Last Z value to be used for track starts (none)
RINC(3) Increment for Z value starting positions (none)

OPTS IGROW Flag indicating whether or not to permit particle growth (1=growth, 0=no growth) 1.
IDIR Direction of particle movement (1=forward, -1=backward). If IGROW=1, then IDIR must be 1
SIZCH Flag indicating whether or not to permit halving or doubling of the timestep to achieve desired step distances. (1=yes, 0=no) 0.
SWIND Flag indicating whether or not to use U and V winds from sounding where radar winds are not available (1=yes, 0=no) 0.
RINIT Flag indicating whether or not to initialize particles based on reflectivity at the position. (1=yes, 0=no) 0.
TIMOFF Time offset (minutes) for initialization by reflectivity. If particles are initialized according to the reflectivity and the reflectivity measurements are made at times different from the time of particle initialization, the reflectivity pattern is adjusted in the horizontal according to the storm motion and the offset time. TIMOFF should be positive for reflectivity measurements subsequent to the initialization time, negative for prior measurements. 0.

PLTRN RMIN(1) X minimum for plotting 0.
RMAX(1) X maximum for plotting 80.
RMIN(2) Y minimum for plotting 0.
RMAX(2) Y maximum for plotting 80.
RMIN(3) Z minimum for plotting 2.
RMAX(3) Z maximum for plotting 12.

PLTDV MJR(1) Number of major divisions on X-axis of plot 4.
<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MNR(1)</td>
<td>Number of minor divisions on X-axis of plot</td>
<td>5.</td>
</tr>
<tr>
<td>MJR(2)</td>
<td>Number of major divisions on Y-axis of plot</td>
<td>4.</td>
</tr>
<tr>
<td>MNR(2)</td>
<td>Number of minor divisions on Y-axis of plot</td>
<td>5.</td>
</tr>
<tr>
<td>MJR(3)</td>
<td>Number of major divisions on Z-axis of plot</td>
<td>5.</td>
</tr>
<tr>
<td>MNR(3)</td>
<td>Number of minor divisions on Z-axis of plot</td>
<td>2.</td>
</tr>
<tr>
<td>PTRAJ</td>
<td>Flag indicating whether to do trajectory plots (1=yes, 0=no)</td>
<td>0.</td>
</tr>
<tr>
<td>IDXSIZ</td>
<td>Put particle symbol on plot at each IDXSIZth timestep.</td>
<td>12.</td>
</tr>
<tr>
<td>PPRSP</td>
<td>Flag indicating whether to do perspective plots (0=no, 1=yes)</td>
<td>0.</td>
</tr>
<tr>
<td>IPRSP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EYE(1)</td>
<td>X position of eye for perspective plot</td>
<td>0.</td>
</tr>
<tr>
<td>EYE(2)</td>
<td>Y position of eye for perspective plot</td>
<td>0.</td>
</tr>
<tr>
<td>EYE(3)</td>
<td>Z position of eye for perspective plot</td>
<td>0.</td>
</tr>
<tr>
<td>IPRJ</td>
<td>Which plane to project lines of trajectory (1=XZ plane, 2=YZ plane, 3=XY plane)</td>
<td>3.</td>
</tr>
<tr>
<td>NPRSP</td>
<td>Frequency of projection into IPRJ plane (every NPRSPth timestep)</td>
<td>12.</td>
</tr>
<tr>
<td>PTIME</td>
<td>Delta Z (km) used for plotting levels of cloud (if, 0, then no time-plots)</td>
<td>0.</td>
</tr>
<tr>
<td>TIM(I)</td>
<td>Array of times (up to 8) at which to do position plots (minutes from initialization)</td>
<td>(none)</td>
</tr>
<tr>
<td>PLEVEL</td>
<td>Frequency of time (min.) to do level plots (if 0, then none)</td>
<td>0.</td>
</tr>
<tr>
<td>DELTT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEV(I)</td>
<td>Array of levels (up to 8) at which to do position plots (km above sea level)</td>
<td>(none)</td>
</tr>
<tr>
<td>PINIT</td>
<td>Code for initial position plot</td>
<td>(none)</td>
</tr>
<tr>
<td>IOVR(I)</td>
<td>Code for overlay for corresponding initial position plot</td>
<td>(none)</td>
</tr>
</tbody>
</table>

Note: The format of this card is (9A8). Up to 4 pairs of IPOS, IOVR (or FPOS, FOVR) may be specified on 1 card. More pairs may be specified on subsequent cards. (The code PINIT (PFINL) is optional on the subsequent cards if they immediately follow the first.) As many as 40 pairs may be given. Possible codes for the plots are:

- FINLDC: Diameter at end of trajectory
- FINLXC: X position at end of trajectory
- FINLYC: Y position at end of trajectory
- FINLZC: Z position at end of trajectory
- FINLREF: Reflectivity at end of trajectory
- MAXDC: Maximum diameter during trajectory
- MAXZ: Maximum altitude during trajectory
MAXREF  Maximum reflectivity during trajectory
MAXLW  Maximum liquid water content during trajectory
MAXW  Maximum vertical velocity during trajectory
TIME  Total time (min) of trajectory
ENCODE  End code (reason for trajectory termination)

Possible codes for the overlays are:

(blank)  No overlay
REF  Radar reflectivity field
W  Vertical velocity field
U  U wind field
V  W wind field

Unrecognized codes will be ignored. If a particular position plot is to be done with more than 1 overlay type (including "none") then the given code must be specified once with each overlay designation.

PFINL  PPOS(I) Code for final position plot (none)
FOVR(I) Code for overlay for corresponding position plot (none)

Note: Refer to note for PINIT.

PSIZE  SOVR  Code for overlay for final position-size plots (none)
PSIZE(I) Array (up to 8) of critical sizes (cm) for the final position-size plots (none)

Note: The format is (2A8, 8F8.0). Overlay codes are as specified above. If more than one overlay type is desired, additional PSIZE cards with desired overlay codes included and the numeric fields blank may be given.

OVRLA  OCODE  Code for overlay field to be used, REF
CMIN  Minimum value to be contoured in field OCODE  5.
CMAX  Maximum value to be contoured in field OCODE  75.
CINC  Increment for contours  10.
CTIME  Time (elapsed minutes) to use for overlay of final position plots (relevant only if more than 1 radar volume used)  30.

Note: The format is (2A8, 4F8.0). The overlay codes are as given above. One card must be included for each overlay type that is used in the initial and final position plots.
Appendix B. Sample Decks

Sample deck for one-dimensional model. In this case, the model is run in changing conditions in a cloud described by the sounding taken at Miles City on 1 August 1981 at 163000. The sounding will be read from the COCOPE rawinsonde tape on unit 7. Ten-second timesteps will be used, and the particles will run for a maximum of 25 min. Data will be printed every 6th step (1 min.). Parameter plots will be done showing terminal velocity values. Temperatures and vertical velocities will be taken from the sounding, but constant liquid water contents of 0. and 1. will be substituted. For dendrites, four initial diameters will be used, and each will be initialized at the two given temperatures. This first run subset will initialize a total of 16 particles (4 diameters * 2 temperatures * 2 liquid water contents). In the second run subset, three different diameters of columns will be initialized at each of two temperatures (12 total). In the last subset, the same diameters will be used again for bullet rosettes, at one temperature (six total).

JOB,JN=username,US=usernumber,T=100,OLM=150,*TB,*D1.

* 1D AND GROWTH MODELS

* GET THE FORTRAN FILES FROM PSTORE
PCOPY ( FROM=/TB/JPARRISH/MODEL/M1DA,FOR,GROWA,FOR,SOUND,FOR,TRANSPLT,FOR;
TO=M1D,MGR,SND,TRANS )

* TO DISPOSE THE PRINTED OUTPUT TO THE IBM PRINTER WHEN DONE
DISPOSE,DN=$OUT,SDN=DUM1,MF=IO,DC=PR,DEFER.

* GET THE COCOPE SOUNDING TAPE FROM MASS STORAGE
ACQUIRE,DN=UNIT7,PDN=RSG83,MF=TB,TEXT='ONLINE'.
ASSIGN,DN=UNIT7, A=FTO7.

* ASSIGN THE PLOT FILE FOR THE PARAMETER PLOTS
ASSIGN,DN=$PLT.
* EDIT, COMPIL E, AND EXECUTE
EDITOR.
CFT, I-MODEL1D, ON=0, L=0.
LDR, SET=INDEF.
*
* DISPOSE PLOT FILES TO DICO MED FOR 35MM MICROFILM
NETDISP, DN=$PLT, DF=BI, MF=D1, DC=PT, MDS, TEXT='CAMERA=FiLM'.
EXIT.
\EOF
EDIT, D-MODEL1D
FETCH, S=M1D
FETCH, S=MGR
FETCH, S=SND
FETCH, S=TRANS
\EOF
*CODEXXX111111112222222233333334444444455555555666666667777777777888888899999999
*TIME STEP-SEC # MIN RUN
TIME 10. 25.
*PRINT EACH 6TH STEP (1 MIN)
PRINT 6.
*MOVE IN UPDRAFT
MOVE
*SOUNDING UNIT (TAPE) DATE TIME LOCATION
SOUND 7. 1. 810801. 1630. MILES CI
*CLOUD BASE PRES ALT TEMP MIX.RAT
CLOUD 711. 3000. 12.0 11.2
*PARAM.PLOT - TERM VEL
PLPRM VT
*CONSTANT LIQ. WATERS
LW 0. 1.
*HABIT DENDRITE
HABIT 1.
*DIAM (INIT)
DIAM 0.01 0.05 0.1 0.2
*TEMP (INIT)
TEMP -12. -17.
GO
* NEEDLE
HABIT 8.
DIAM 0.01 0.05 0.1
GO
* BUL.ROSETTE
HABIT 9.
TEMP -25.
GO
DONE
\EOD
Sample deck for three-dimensional model. Two radar volumes will be used, the first one for 13 min., the second for 27 min., for a total of 40 min. run time. Storm movement is 8.9 m/s U and 3.6 m/s V. The radar data are ground relative. The lowest level to be used is 0.8 km. The sounding will be read from the CCOPE sounding tape on unit 7; the sounding is from 12 June 1981 at Miles City. Particles will be initialized over a grid from -5 to +10 on the X-axis, 52 to 62 on the Y-axis, and 5 to 10 on the Z-axis, all at 1-km intervals (total 1056 points). The plotting grid for the trajectory, time, and level plots will be -13 to 27 X, 42 to 82 Y, and 1.8 to 10.8 Z. Standard trajectories will be plotted, with a symbol indicating the size and state of the particle each 12th step (2 min.). A listing on film will give the particle information each 6th step (1 min.). Time plots will be done at 0, 10, 20, 30, and 40 min. showing the storm levels each kilometer. Level plots will be done for 0.8 km at intervals of 5 min. Initial-position plots will be done showing final diameter overlaid with both reflectivity and vertical velocity. Final-position plots will show final diameter alone and with reflectivity overlaid. Final position-size plots will be done for critical sizes of 0.5 and 1.0 cm, all overlaid with reflectivity contours. Particles will be initialized for both habits 1 and 4, each at three diameters (total six different particles -- 6336 possible initializations).

JOB,JN=username,US=usernumber,T=300,OLM=50,*TB,*D1.

* 3D AND GROWTH MODELS *
* GET THE FORTRAN FILES FROM PSTORE 
PCOPY ( FROM=/TB/JPARRISH/MODEL/TRAJA.FOR,GROWA.FOR,RADAR.FOR,SOUND.FOR; 
TO=M3D,MGR,CARTIO,SND )
* GET RADAR DATA FROM MASS STORAGE
ACQUIRE,DN=UNIT10,PDN=SYNO84,MF=TB,TEXT='ONLINE'.
ASSIGN,DN=UNIT10,A=FT10.
ACQUIRE,DN=UNIT11,PDN=SYN154,MF=TB,TEXT='ONLINE'.
ASSIGN,DN=UNIT11,A=FT10.
*
* GET THE CCOPE SOUNDING TAPE FROM MASS STORAGE
ACQUIRE,DN=UNIT7,PDN=RSNG83,MF=TB,TEXT='ONLINE'.
ASSIGN,DN=UNIT7,A=FT07.
*
* ASSIGN THE PLOT FILE
ASSIGN,DN=$PLT.
*
* EDIT, COMPILE, AND EXECUTE
EDITOR.
CFT,I=MODEL3D,ON=O,L=O.
LDR,SET=INDEF.
*
* DISPOSE PLOT FILES TO DICOMED FOR 35MM MICROFILM
NETDISP,DN=$PLT,DF=BI,MFD1,DC-PT,MDS,TEXT='CAMERA-FILM'.
EXIT.
\EOF
EDIT,D=MODEL3D
FETCH,S=M3D
FETCH,S=MGR
FETCH,S=SND
FETCH,S=CARTIO
\EOF
*CODEXXX11111111222222223333334444444555555556666666666666667777777788888888888999999999
*TIME STEP-SEC
TIME 10.
*
* WIND(RADAR) UNIT REWIND # MIN VOL REFL U V W
WIND 10. 1. 13.UNKNOWN DZ2 U V WS
WIND 11. 1. 27.UNKNOWN DZ2 U V WS
*STORM MOVE U V GRND REL
SMOVE 8.9 3.6 0.
*ZOUT BOTTOM ALT
ZOUT 0.8
*SOUNING UNIT TAPE DATE TIME LOCATION
SOUND 7. 1. 810612. 1640.MILES CI
*CLOUD BASE PRES ALT TEMP MIX.RAT
CLOUD 745. 3000. 11.0 11.2
*DROP DIST. SIGSQ DCONC
DROP 25. 600.
*INIT LOCS XMIN XMAX INC YMIN YMAX INC ZMIN ZMAX INC
XYZ -5. 10. 1.0 52. 62. 1.0 5.0 10.0 1.0
*PLOT RANGE XMIN XMAX YMIN YMAX ZMIN ZMAX
PLTRN -13. 27. 42. 82. 1.8 10.8
*PLOT DIVISIONS
PLTDV  8.  5.  8.  5.  3.  3.
*TRAJ PLOTS YES STEP(2MIN) FILM(1MIN)
PTRAJ  1.  12.  6.
*TIME PLOTS (1KM INTERVALS) TIMES 0, 10, 20, 30, 40
PTIME  1.0  0.  10.  20.  30.  40.
*LEVEL PLOTS (5MIN INTERVALS) AT 0.8 KM (GROUND)
PLEVL  5.0  0.8
*INIT POSITION PLOTS
PINIT FINLD REF FINLD W
*FINAL POSITION PLOTS
PFINL FINLD REF FINLZ REF
*FINAL POSITION/SIZE
PSIZE REF  0.5  1.0
*OVERLAY SPECS
OVERLA REF  5.  75.  10.  35.
W  -5.  25.  5.  35.
* DENDRITE GRAUPEL
HABIT  1.  4.
* INIT DIAMS
DIAM  0.01  0.05  0.1
GO
DONE
\EOD
Appendix C. Descriptions of the Subroutines

A. 1D

PROGRAM GROW 1D controls calculations describing the growth of a particle in a one-dimensional (vertical) cloud.

SUBROUTINE DATAIN reads a set of input cards to determine setup of a 1D run.

SUBROUTINE SOUND returns the temperature, mixing ratio, and pressure associated with the altitude \( Z \), from the input sounding. ENTRY INSOUND reads the input sounding, or calls the sounding package to read it from tape.

SUBROUTINE STATE interpolates the tables of atmospheric conditions, to get pressure, temperature, liquid water content, and vertical velocity.

SUBROUTINE THERMO1 does the thermodynamic calculations. From the input sounding arrays of temperature, pressure, altitude, and mixing ratio, it sets up the arrays of temperature, pressure, altitude, liquid water content, and vertical velocity used by subroutine STATE.

SUBROUTINE VAPRES calculates vapor pressure with respect to water and ice.

B. 3D

PROGRAM TRAJ 3D controls the calculations of the three-dimensional particle growth model.

SUBROUTINE DATAIN reads the input data and sets up parameters for the run.

SUBROUTINE GETUVW gets the appropriate wind field data, unpacks it, and returns the interpolated U,V,W and reflectivity, given the location X,Y,Z and time. ENTRY GETUVWI calls the routines which read the Doppler radar tapes, then packs the data, and stores it for later recall.

SUBROUTINE INITDBZ implements the option to determine particle initialization based on reflectivity at the point. It uses routines ISTART, ISTART1, and ITEMP.

SUBROUTINE ISTART determines the probability of a particle of given habit and diameter occurring at a position, given the reflectivity. If that probability is greater than the prescribed threshold, then the routine indicates that the particle should be initialized there.

SUBROUTINE ISTART1 is used with subroutine INITDBZ in determining initialization of dendrites and aggregates.
SUBROUTINE ITEMP determines maximum initial size for dendrites given environmental temperature. If the indicated diameter is more than twice the maximum possible size, then the particle is not initialized.

SUBROUTINE SKIPF positions the desired unit at the beginning of the indicated file number.

SUBROUTINE SOUND returns the temperature, pressure, and liquid water content, given the altitude and vertical velocity.

SUBROUTINE TRACK controls the particle movement, and calls the growth routines.

SUBROUTINE WRXYZRT writes the trajectory information to disk for later use. ENTRY RDXYZRT reads the desired trajectory from disk.

PLOTTING ROUTINES

SUBROUTINE OVERLAY controls the contour overlays for the initial and final position plots.

SUBROUTINE PLOTTR plots the trajectories of the particles projected on the desired plane.

SUBROUTINE PLOTSET sets up the plot and does some of the labeling. ENTRY PLOTSTI does initialization of the scale factors needed for the plotting.

SUBROUTINE PLTPART determines the size range of the particle and plots size and habit information at the given point. ENTRY PLTPRTI sets up a plot buffer with size and habit information.

SUBROUTINE PLTSIZ plots a number giving some information about the particle at the given position.

SUBROUTINE SIZPLTS controls the initial- and final-position plots.

SUBROUTINE SORTI does a sort on the input array, and returns an index array giving the array ordering. Called by TIMPLTS.

SUBROUTINE TIMPLTS reads the data for each particle at a specified time or level, and plots them by constant-level planes, or constant times.

C. GROW

SUBROUTINE CALC1 calculates the various parameters needed for the growth rate and particle temperature calculations for a time period.

SUBROUTINE VTDROP calculates terminal velocities for the cloud droplets.
SUBROUTINE GROW controls the particle growth calculations. ENTRY
GROWI does the particle initialization.

SUBROUTINE INITS calculates the initial thickness, volume, density,
and mass, given the initial diameter and particle habit.

SUBROUTINE KAXIS figures the initial axis ratio and density, in cases
where these are a function of temperature.

SUBROUTINE FILLI figures the volume and area of the filled-in parti-
cle.

SUBROUTINE AREAS calculates the area and shape factor of a particle.

SUBROUTINE XRE calculates the Best number (X) and Reynolds number (RE)
of a particle for determining its terminal velocity.

SUBROUTINE VT calculates the terminal velocity of a particle, given
the Reynolds number and dimension.

SUBROUTINE CETCEF calls the collection efficiency subroutine. In some
cases, it sets up a special "transition line" to do this.

SUBROUTINE COLEFF calculates the collection efficiency of the particle
for each of 15 sizes of water droplets.

SUBROUTINE ACCR calculates effective liquid water content and the
particle's accretional growth rate.

SUBROUTINE PTEMP calculates the particle temperature and diffusional
growth rate.

SUBROUTINE VENTC calculates the ventilation coefficient of the parti-
cle.

SUBROUTINE PTEMP1 iterates to find the particle temperature and rates
of change when the particle is not in normal growth mode (i.e., it is soak-
ing, melting, or freezing residual water).

SUBROUTINE ADDMASS determines the amount and density of particle
growth (both frozen and liquid) based on the particle status.

SUBROUTINE AGGRO determines the growth of aggregates due to aggrega-
tion (optional).

SUBROUTINE GROWD allows for the growth in diameter of un-filled-in
dendrites, columns, or bullet rosettes, due to diffusional growth. Used in
dry growth conditions only.
SUBROUTINE G2 does calculations for GROWD.

SUBROUTINE WET calculates the amounts soaked, accumulated, and shed of the liquid water present.

SUBROUTINE DIMS calculates the diameter and thickness of a particle, given its volume.

SUBROUTINE TRANSIT determines where the particle is in relation to the various habits and controls the transitions between habits.

SUBROUTINE TRANSI calculates the final dimension and some associated parameters used during the transition of a particle from a dendrite or column to a sphere.

FUNCTION PROFILE calculates a value for temperature or relative humidity, given altitude, and constants A and B defining the profile. Use is optional.
REFERENCES


Sci., 33, 842-850.