An Examination of Double-Plate Ice Crystals and the Initiation of Precipitation in Continental Cumulus Clouds

ROELOF T. BRUINTEJS

South African Weather Bureau, Bethlehem 9700, Republic of South Africa

ANDREW J. HEYMSFIELD

National Center for Atmospheric Research, Boulder, Colorado 80307*

TERRENCE W. KRAUSS†

South African Weather Bureau, Bethlehem 9700, Republic of South Africa

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ABSTRACT

Measurements within continental convective clouds in the Highveld region of South Africa indicate that the first appreciable nucleation of ice occurs between the −9° to −12°C levels as the cloud top rises through these levels. Moreover, these crystals usually take the form of double plates. Frozen drop centers were observed in 30% of the double crystals, with the diameter of the frozen drop between 10 and 20 μm. The growth of these ice crystals is investigated using ice crystal measurements collected in situ as well as a modeling study.

New information regarding axial dimensions, bulk densities, and riming characteristics of double-plate crystals is presented. Numerical simulations were performed to compare the growth characteristics of ice crystals nucleated at different temperature levels between −6° and −16°C in updrafts of 1 and 3 m s⁻¹. Crystals nucleated at temperatures ≥ −12°C are shown to start riming at smaller sizes than previously thought and these crystals are potentially important as graupel embryos in initiating precipitation in growing cumulus congestus clouds.

1. Introduction

In the Highveld region of South Africa, precipitation in summertime convective clouds typically develops via the ice phase (Carte, 1960). Measurements in these clouds indicate that the first ice typically nucleates around the −10°C level and that these crystals usually take the form of double plates.

The existence of double-plate ice crystals in the atmosphere has been reported in the literature (Nakaya et al., 1936; Weickmann, 1947; and Aufm Kampe et al., 1951). Frequently, frozen drops were inferred to be the centers of these ice crystals. Replicas of planar ice crystals with frozen drop centers collected within a mountain cap cloud were first observed by Auer (1970, 1972). Heymsfield (1973) and Parungo and Weickmann (1973), in laboratory experiments, also showed the development of double crystalline structures nucleated from frozen drops. Fukuta (1980) and Fukuta et al. (1982), in their laboratory experiments, showed double plates to form between −10° and −12°C. Ryan et al. (1976; their Fig. 3) referred to double skeletons, although they did not elaborate in the text. Results obtained in a recent study by Iwai (1983) indicated that most planar ice crystals consist of two or more plates which have different forms and sizes.

Numerical models of ice crystal growth (e.g., Hindman and Johnson, 1972; Miller and Young, 1979; Strapp et al., 1979; Heymsfield, 1982) and some laboratory studies (Ryan et al., 1976; Fukuta, 1969) fail to differentiate between thick plates and double plates within the temperature range of −9° to −12°C. Instead, the three-dimensional structure of the ice crystals is accounted for by assuming the crystals to be thick plates.

The present study attempts to clarify some of the growth features and riming properties of double-plate crystals. New ice crystal data collected in situ are compared with previous studies and a model is employed to interpret the data. Evidence is presented indicating that double-plate ice crystals start riming at smaller sizes than previously thought and that these ice crystals are potentially important as graupel embryos in initiating precipitation in cumulus clouds.

2. Observations

The data for this study were collected during field experiments as part of the Bethlehem Precipitation

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† Present Affiliation: Alberta Research Council, Edmonton Canada.

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Research Project during the 1983/84 and 1984/85 summer seasons. The research was conducted in the northeastern parts of the Orange Free State in South Africa. Approximately 85% of the 680 mm annual precipitation falls in the summer months between October and March. Nearly 80% of this rainfall is the result of convective activity.

a. Instrumentation

Ice crystals were collected on oil-coated slides exposed in a deaccelerator on the research aircraft (Aercobommander 690A). The deaccelerator (sample volume of approximately 61 s⁻¹), mounted on top of the fuselage, produces a deacceleration of about 11.1 giving a typical impact velocity of about 9 m s⁻¹. The crystals were preserved in automotive brake fluid until they could be photographed under a microscope in a tray filled with hexane. For photographing the ice crystals from different angles, a needle was used to turn the crystals and flip them over. These measurements provided information on the three-dimensional structure of the ice crystals and their habits, and on whether the particles were rimed. Other instrumentation provided measurements of temperature, humidity, static pressure, air speed, and vertical air motions. A Johnson-Williams (JW) probe was used for measuring liquid water content, a forward-scattering spectrometer probe (FSSP) was used to measure droplet spectra and 1D-C and 2D-C probes were used for ice crystal concentrations.

The FSSP and the 1D-C were calibrated regularly by measuring the sample area and checking the sizing with the use of glass beads of known size. Electronic delay time and coincidence losses for the FSSP were accounted for by software. Routine bench checks of the 2D-C probe also assured that it operated within the manufacturer's specifications. In all cases the manufacturer's sampling volume (including the correction for depth of field) were used for the calculations of the concentrations.

The oil-coated slides were exposed to the airstream for between 1 and 30 seconds depending on the ice crystal concentrations measured by the 2D-C probe. At concentrations < 1 1⁻¹, the slides were exposed for 20 to 30 s, and at concentrations > 100 1⁻¹ for 1 s only.

During the analyses of the slides, every crystal that was clearly identifiable was flipped on its side to study its three-dimensional structure. The number of crystals studied in this manner on each oil-coated slide varied between one and 20, depending on the concentration of crystals. Roughly 500 crystals were studied altogether. It was also possible to distinguish between single and double crystals by focusing on each crystal separately under the microscope.

b. Cloud characteristics

The summertime convective clouds in the Highveld region of South Africa are continental in nature. The clouds studied were semiisolated cumulus congestus clouds in their growing stages, well separated from large thunderstorms or line storms. The average convective cloud base temperature for the 1984/85 summer season was 7.7°C, with an average pressure of 675 mb, compiled from measurements made on 75 days when convective clouds and precipitation occurred. Measurements with the FSSP in 30 clouds near the −10°C level during 8 days in February 1985, indicated a continental cloud droplet distribution. The modal values for cloud droplet concentration, mean volume diameter, and coefficient of dispersion were 1000 cm⁻³, 14 μm, and 0.4, respectively. The mean value for the 1 km horizontally averaged liquid water content, measured by the JW probe in 56 clouds between October 1984 and March 1985 at the −10°C level, was 1.3 g m⁻³, with no marked variation between the individual months. Maximum updraft velocities varied between 1 and 5 m s⁻¹. Measurements of the ice crystal concentrations were made on 24 different days between January and March 1985, around the −10°C (±2°C) level in developing cumulus congestus clouds, within 300 m of cloud top. The measurements were obtained with a 1D-C probe and only particles > 50 μm were taken into account. These results indicate that ~40% of the clouds contain ice concentrations of more than 1 1⁻¹ and ~70% of the clouds have concentrations of more than 0.1 1⁻¹. The cloud lifetimes in 60 cumulus congestus clouds studied during the 1984/85 season were found to be about 18 min. The median “time window” for liquid water values larger than 0.5 g m⁻³ was about 10 min.

c. Primary ice

Analyses of 108 oil-coated slides collected on 14 days during the 1983/84 summer season and 32 days during the 1984/85 summer season, between the −5°C and −15°C levels in developing convective clouds, indicate that double-plate and isometric ice crystals are the predominant crystal habit and represent the natural “first ice”. No ice crystals were observed on oil-coated slides collected in clouds with tops warmer than −8°C, which supports the early studies conducted by Carte (1960). Oil-coated slides exposed between the −12°C and −15°C levels collected crystals with a double-plate structure with branches. These observations are consistent with the laboratory results of Fukuta et al. (1982), indicating that double-plate ice crystals form in the −10°C to −12°C temperature regime. The analyses indicated that 90% of all first-ice crystals were double-plate crystals, while columns and single plates comprised <10% of all crystals observed. A typical example of double crystals collected on an oil-coated slide from a developing cumulus cloud is displayed in Figs. 1a and 1b. Hexagonal plates are the predominant crystal type (Fig. 1a), while most possess a double structure exemplified by the crystal flipped on its side in Fig. 1b.

The center, serving as the link between the two plates,
consists of either a small hexagon or a sphere, presumably a frozen cloud droplet. Double plates with frozen drop centers were positively identified in approximately 30% of all the crystals studied. The diameters of the frozen drops varied between 10 and 20 μm. An example of a double plate with a small hexagon as its center is shown in Fig. 2a, while an example of a crystal with a frozen drop center is displayed in Fig. 2b. Both crystals were collected near the −10°C level. The initial stage of rime collection is also evident, mostly confined to the edges.

The two plates of a double-plate crystal with branches grow simultaneously up to a certain size (generally between 200 and 300 μm along the a-axis) in more than 80% of the branching crystals that were analyzed. At larger sizes, growth is preferentially along one crystal, although symmetric growth can also occur. Examples of the symmetric and preferential growth are displayed in Figs. 3a–d. The reason for preferential growth after a certain period (Figs. 3c and d), is not yet fully understood. Fukuta et al. (1982) argued that double plates tend to shift into single plates due to the moisture blocking by the lower plate while they are falling. Iwai (1983), on the other hand, found that these crystals usually fall with the smaller plate oriented downward. The reason Iwai gives for the preferential growth is that with the smaller plate oriented downward, supersaturation at the central part of the crystal is lower than that at the periphery (corners). Consequently, the lower, smaller plate grows more slowly under a condition of lower supersaturation than the larger plate on the top (Kuroda, 1982). Iwai also argues that ventilation at the central part of the snow crystal is not effective. In the example shown in Fig. 3d, it appears that for a period of time the crystal fell with its small plate oriented downward; the evidence for this is the riming that is visible on the inner side of the large plate. The fall attitude of individual crystals is an important parameter when the riming characteristics of the crystals are considered. The size at which double plates tend to develop into double plates with branches evidently depends mainly on the length of time the double plates remain in the −9°C to −12°C growth regime before they are carried to colder temperatures.

Two parameters that play an important role during the diffusional growth stage—the ice crystal axial ratio and the bulk density—were determined from the crystals collected on oil-coated slides. The axial ratios of the double-plate crystals were calculated by adding the thickness (length along the c-axis) of each plate (ex-
including the air gap) and dividing this quantity by the diameter (maximum length along the a-axis) of the crystal. If the thickness or diameter of a double-plate crystal could not be measured accurately due to riming, it was omitted from the sample. A scatter diagram of the crystal axial ratio versus diameter is presented in Fig. 4, compiled from 65 particles with diameters < 500 μm. The mean axial ratio was 0.23, with a standard deviation of 0.09.

The bulk density was calculated as the volume of the two plates plus the volume of the center droplet divided by the total crystal volume (incorporating the air gap in the thickness) and multiplied by the density of solid ice (i.e., 0.91 g cm\(^{-3}\)). The calculated bulk densities of 60 particles as a function of diameter, for diameters < 200 μm, is presented in Fig. 5. At these sizes, crystal faces are complete hexagons instead of hexagons with branches. The mean bulk density was 0.58, with a standard deviation of 0.09, which agrees well with the estimated values (approximately 0.65) obtained by Ryan et al. (1976).

To fit a line to the bulk-density and axial-ratio data as a function of diameter, the mean values were calculated in seven different size categories. The data are displayed in Fig. 6 for the crystal axial ratios (excluding the air gap), and the total crystal thickness (including the air gap) divided by the diameter (total ratio) ("Total Ratio") for particles up to 500 μm diameter. The variation of bulk density for diameters up to 200 μm is also displayed in Fig. 6. Bulk densities for larger crystals were not calculated due to the difficulty in estimating the exact surface area for ice crystals with branches. The variation of bulk density with diameter is consistent with previous experiments (Heymsfield, 1972; Ryan et al., 1976). According to the data presented in Fig. 6, there is a slight dependence of axial ratio with diameter, with a maximum axial ratio of 0.26 at diameters between 50 and 100 μm, decreasing to 0.09 for diameters > 400 μm. The total crystal thickness-to-diameter ratio for diameters between 50 and 150 μm is 0.36. Because Ryan et al. (1976) calculated their axial ratios using the total thickness (including the air gap) of the crystal, our value of 0.36 compares favorably with the value of 0.36 obtained by Ryan et al. after 150 s of growth. Miller and Young (1979) used a total thickness-to-diameter ratio of 0.33 at -11°C in their modeling study. All these results show excellent agreement between the laboratory studies and the present field observations when the crystal is considered to be a thick plate incorporating the air gap.

The ratio of the “filled in” basal plane area to the total basal plane area of a complete hexagon with the same diameter (length along a-axis) was calculated for a sample of 23 double plates with branches which were
Fig. 3. (a) Plan view and (b) side view of a double-plate crystal with branches showing symmetric growth, and the (c) plan and (d) side view of a double-plate crystal with branches showing preferential growth. The full scale represents 1 mm and the distance between two lines corresponds to 100 μm.
larger than 200 μm. The ratio decreased from approximately 0.85 for crystal diameters < 300 μm to about 0.7 for diameters around 1 mm. The crystal basal plane area as a function of diameter is shown in Fig. 7. According to the relationship found in Fig. 7, branching crystals with diameters of 1 mm will have a basal plane area of approximately 0.37 mm² as compared to 0.2 mm² found by Takahashi (1986) at temperatures from −12° to −16°C. This would suggest that the crystals in the present study, developed broader branches than the crystals studied by Takahashi.

The present results obtained from measurements at an approximate pressure level of 500 mb [compared to Ryan et al.'s (1976) data at 1000 mb] suggests that the axial ratios and bulk densities are consistent and nearly independent of atmospheric pressure. The linear growth rates, however, are pressure dependent.

d. Riming properties of ice crystals

The sizes at which ice crystals start to collect supercooled cloud drops is an important parameter when studying precipitation development in clouds. Ono (1969), Harimaya (1975), and Reinking (1979), among others, have studied this parameter. Harimaya and Reinking based their results on surface observations, while Ono also incorporated airborne observations in his study. Both Ono and Harimaya classified their
crystals as rimed crystals whenever the crystal accreted five or more droplets. This classification is used in the present study.

Although a minimum in the growth rate is experienced in the $-9^\circ$ to $-12^\circ$C temperature regime (Ryan et al., 1976), the crystals formed in this range tend to grow into either isometric or double structures, which are apt to be better rimers at smaller sizes than single plates, dendrites, or needle crystals (Fukuta et al., 1982). This effect, due to the higher terminal velocities experienced by these particles, was demonstrated by the calculations of Heymsfield (1982) for graupel growth.

In this section, the onset and stages of riming of crystals growing in the $-9^\circ$ to $-12^\circ$C region are described. The riming characteristics of 122 rimed isometric and double-plate crystals collected on oil-coated slides were studied. The crystals were classified into three categories as a function of diameter, namely

(i) lightly rimed (more than five drops accreted but crystal still clearly identifiable)

(ii) moderately rimed (crystal face covered with rime but still identifiable)

(iii) heavily rimed (crystal not identifiable due to rime coverage)/graupel particles

The data are summarized in Fig. 8, which indicates that some crystals with diameters < 100 μm were found to be lightly rimed (i.e., more than five drops accreted). These crystals had an isometric or nearly isometric form. An example of a lightly rimed double plate and a nearly isometric ice crystal are displayed in Figs. 9a, b, and c (b represents a side view of the double plate). The major axis of the isometric crystal is about 80 μm while the diameter of the double-plate crystal is about 150 μm. Another example of rimed, nearly isometric crystals is shown in Fig. 10a. Some of the crystals are heavily rimed. Heavily rimed crystals and small graupel particles are displayed in Fig. 10b, while a heavily rimed plate is shown in Fig. 10c. Looking back at Fig. 8, it is evident that heavily rimed crystals were first observed in the size category 150 to 200 μm. The crystals with

![Graph](image-url)

**Fig. 8.** Rimming characteristics of 122 rimed isometric and double-plate ice crystals. Crystals are classified into three categories—lightly rimed, moderately rimed, and heavily rimed—as a function of diameter (maximum length along a-axis).
Fig. 9. (a) Plan view of a lightly rimed double-plate ice crystal; (b) a side view of the same crystal; (c) a lightly rimed, nearly isometrical crystal. The length of the scale represents 1 mm and the distance between any two lines is 100 μm.
Fig. 10. (a) Examples of rimef isometric ice crystals, (b) small (~200 to 300 μm diameter), heavily rimed crystals and graupel particles and (c) a heavily rimed double plate, collected on the oil-coated slides near the -10°C level. The length of the scale represents 1 mm and the distance between any two lines is 100 μm.
diameters less than 100 $\mu$m that were lightly rimed were mostly isometric crystals as shown in Figs. 9 and 10a. Lightly rimed double plates were first observed on the oil-coated slides in the size range between 100 and 150 $\mu$m.

A similar rime analysis was done for double-plate crystals with sector-like branches. The sample consisted of 46 crystals, all with a double-plate structure. The results are displayed in Fig. 11. No crystals with sector-like branches with diameters $< 250$ $\mu$m had collected any rime. However, lightly, moderately, and heavily rimed crystals with sector-like branches were observed in the size range 250 to 300 $\mu$m. Most crystals with sector-like branches started to rime when their major axis (length along the a-axis) was larger than 300 $\mu$m. A typical example of a moderately to heavily rimed crystal with sector-like branches is displayed in Fig. 12. The onset size of approximately 300 $\mu$m for these crystals agrees favorably with the observational studies of Ono (1969) and Harimaya (1975), who also found the rime-onset diameter of these crystals to be around 300 $\mu$m. Reinking (1979) found a rime-onset diameter of $\sim 240$ $\mu$m for these crystals.

Neither Ono, Harimaya, nor Reinking considered the onset sizes for riming of isometric and double-plate crystals. However, Fukuta (1980) and Fukuta et al. (1982) suggested that crystals growing in the $-9^\circ$ to $-12^\circ$C temperature regime might be the best candidates for graupel formation; it was within this zone, their laboratory studies showed, that ice crystals fell fastest and thus presumably attained the highest collection efficiencies. Crystals would thus start riming at smaller sizes and develop into graupel by accretion faster than crystals at other temperature levels. The present study supports this finding. Another possible factor that might influence the riming capabilities of crystals growing in this temperature regime is the quasi-liquid layer that covers the surface of the crystals in this region (Lacman and Stranski, 1972; Kuroda, 1982). The quasi-liquid layer enhances the riming capabilities of the crystals (Parungo and Weickmann, 1983). Also, Ono (1969) found that columns must be

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**Fig. 11.** Rimming characteristics of 46 rimed double plates with branches. Crystals again are classified into the same categories as for double-plate crystals (Fig. 8) and presented as a function of diameter (maximum length along a-axis).
3. Numerical Model Description

a. General

A numerical ice-growth model developed by Heymsfield (1982) was used to simulate the growth of ice crystals of various habits through vapor diffusion and liquid water accretion. The physics of the model is discussed in Parrish and Heymsfield (1985). For planar, needle, and columnar crystals, the crystal axial ratios and densities are function of the temperature based upon the laboratory experiments of Ryan et al. (1976). The crystal mass is derived assuming the particles are hexagonal. Fall speeds for the particles are calculated using a Best number (X)–Reynolds number (Re) approach whereby relationships are formulated between X and Re for each of the particle types. The Heymsfield model is modified to simulate double-plate crystals in the following manner.

b. Crystal mass and dimensions

Previous modeling and laboratory studies (Ryan et al., 1976; Miller and Young, 1979; Hall, 1980; Cooper and Lawson, 1984) used axial ratios of crystals for the $-10^\circ$ to $-12^\circ$C range based upon the maximum measured dimensions along the $a$ and $c$ axes. This approach does not take into account the air gap between the crystals for double plates and thus it overestimates the length along the $c$-axis. In the Heymsfield (1982) model, the dimensions along the $c$-axis for double-plate crystals is taken as the sum of the thicknesses of each of the two plates excluding the air gap between the crystals. The densities of each plate is taken to be 0.91 g cm$^{-3}$.

In section 2 it was shown that the axial ratios calculated by Ryan et al. and those calculated from the present observational data differ only slightly by assuming the

![Fig. 12. Example of a moderately to heavily rimed crystal with sector-like branches. The length of the scale represents 1 mm and the distance between any two lines is 100 μm.](image)

about 70 μm thick in order to start riming, and both Ono and Reinking (1979) have commented that capped columns are the best rimers.

The $P$ ratio, defined as the ratio of the largest rimed cloud droplet diameter to the crystal diameter, was derived for rimed double plates collected on 24 different oil-coated slides. No double plates with rime were observed at crystal diameters < 70 μm. The $P$ ratios were specifically incorporated because the model, discussed later, generates a log-normal cloud droplet distribution using the number concentration and coefficient of dispersion, discussed earlier, as the input parameters. The model thus generates cloud droplets $> 30$ μm, which will reduce the onset size for riming of crystals in the model, due to higher collection efficiencies, with these cloud droplets. Consequently, the sizes of the largest cloud droplets that rimed on the crystals on the slides were determined and the $P$ ratio calculated to exclude the onset of riming for cloud droplets beyond a certain diameter in the modeling studies (e.g., see Beard and Grover, 1974). The results are presented in a scatter diagram in Fig. 13. The mean $P$ ratio was calculated to be 0.10, with a standard deviation of 0.037.

![Fig. 13. Scatter diagram for P-ratios (maximum cloud droplet diameter on crystal/crystal diameter) as a function of crystal diameter for double-plate ice crystals.](image)
crystal to be a thick plate (incorporating the air gap). Consequently, we decided to use the Ryan et al. axial ratio data, but to reduce the thickness of the ice crystal to account for the gap between the double plates.

A modification was incorporated in the model to calculate the physical diameter of crystals growing between $-12^\circ$ and $-18^\circ$C. The crystal areas from the field observations in the $-12^\circ$ to $-18^\circ$C temperature range (Fig. 7) were used to calculate crystal area as a function of diameter rather than those implied from the Ryan et al. (1976) measurements. The areas derived in the present study apply to larger sizes and longer growth periods than those considered by Ryan et al.

c. Shape factor calculations

Houghton (1950) argued that the vapor density and temperature fields surrounding an ice crystal, and the mass and heat fluxes to and from the crystal, can be described in a manner analogous to the potential field surrounding a charged conductor of the same shape. McDonald (1963) experimentally determined the capacities of different ice crystal shapes by modeling the crystal forms in brass and measuring the change in capacity of the system when the model was suspended in the center of the large Faraday cage; he then compared these with theoretically obtained values. Theoretically determined values for the electrostatic capacitance $C$ of a conductor can thus be applied to an ice crystal with the same shape in the diffusional growth equation. The theoretical values indicate that the shape factor is a function of the total surface area of the crystal and, according to McDonald, a function also of the total edge and corners of the crystal.

Crystal capacitances are approximated for columnar crystals by the expression for prolate spheroids with a very small minor axis. In the case of a thin hexagonal plate ice crystal, the shape factor can be approximately by that of a thin circular disk of equal area provided that the thickness is <10% of the edge length (McDonald, 1963).

For an ice crystal consisting of two hexagonal plates joined together by either a small hexagon or a frozen droplet, the shape factor for a thin circular disk is probably not appropriate. This approximation would underestimate the growth rate of these crystals, especially during the early growth stages, by excluding the surface area between the plates and the increase in corners and edges, as opposed to a single plate. Although some "shielding" of the vapor flux to the area between the crystals may occur, this factor may not be important at very small sizes where the gap between the crystals is approximately the same dimension as the crystal diameter, and for sizes larger than about 400 $\mu$m when growth of the faces is symmetric. It is reasonable, therefore, to approximate the shape factor as that for an oblate spheroid since the surface area of two thin hexagonal plates is nearly equal to 82% of that of a sphere of the same diameter and the hexagonal plates are not especially thin at small sizes (Fig. 4).

Isometric crystals usually growing between the $-9^\circ$ and $-10^\circ$C levels will have a total surface area larger than that of a sphere with the same cross-sectional diameter. It would thus seem appropriate to use the shape factor of an oblate spheroid for isometric ice crystals as well. The shape factor for all ice crystals growing in the $-9^\circ$ to $-12^\circ$C level was consequently approximated by that for an oblate spheroid.

d. Ventilation coefficient

The approach of Hall and Pruppacher (1976) was used to estimate the ventilation coefficient. Although this approach does not take into account the gap between the plates, it is argued that little ventilation occurs between the plates due to the crystals' fall attitude. This approach will underestimate the effect of ventilation; however, ventilation is considered to be a minor effect at the initial diffusional growth stages of interest here.

e. Accretional growth

The accretion of mass by the collection and subsequent freezing of supercooled cloud droplets is the primary mechanism whereby precipitation develops in the clouds considered in this study. When conducting a comparative modeling study of riming as a function of crystal habit, three parameters—collection efficiency, terminal velocity, and the density of the accreted mass—are of primary importance to the growth of the particle by accretion.

The efficiency with which droplets collide with ice particles was calculated using the mixed Froude number approach by Hall (1980). For columnar and needle crystals (which form from $-5^\circ$ to $-8^\circ$C), values were derived using a parameterization (Parrish and Heymsfield, 1985) based on the numerical calculations of Schlamp et al. (1976). Where crystals grew nearly isometrically (at $-8^\circ$ to $-10^\circ$C), the Beard and Grover (1974) parameterization for spheres was used. For planar crystals (from $-12^\circ$ to $-16^\circ$C) the Hall parameterization, based on the Pitter and Pruppacher (1974) and Pitter (1977) calculations, was applied. Their calculations use the superposition approximation and imply that the relative size ratio of the droplet to the ice particle is small. Since in the calculations the particles are not solid disks, the plate-equivalent diameter (diameter of a circular disk with the same surface area as that of a hexagonal plate) was used rather than the maximum length along this $a$-axis of the hexagonal plate. This is a reasonable approximation according to the laboratory results of Prodi et al. (1981). For graupel, the collection efficiency data for spheres were used (Beard and Grover).

The transition of ice particles into spherical graupel due to the mass added by accretion was modeled in stages for both planar and columnar ice crystals. In
both cases we assumed that, during the first stage, rime produced from accreted liquid water is added only to the minor axis, with the crystal still maintaining a hexagonal form. The crystal can still increase its major axis by diffusional growth during this stage. After the crystal reaches a certain specified axial ratio (≈0.3), rime leads to increasing its minor axis and the crystal develops from a hexagonal form into a spherical graupel particle. Growth after this stage is spherically symmetric. During these stages diffusional growth of the crystal is not suppressed.

An extra limitation was put on accretion by specifying certain $P$ ratios to be fulfilled before collection could commence. The $P$ ratio, i.e., the collected droplet's diameter divided by the diameter (or thickness in the case of columns and needles) of the collector particle, was specified for planar crystals to be smaller than 0.1, while for isometric and double crystals it was set at 0.15. Recall that the measurements (Fig. 13) indicated a mean $P$ ratio of 0.10 (±0.037) for the onset of accretion. For columns, the $P$ ratio must be smaller than 0.2. These limitations are valid considering the narrow cloud droplet spectra usually associated with the clouds studied.

Whenever the ratio of the thickness (length along the $c$-axis) divided by the diameter (length along the $a$-axis) of the crystal exceeds 0.3 and the volume of ice added by accretion exceeded the volume of ice added by diffusion, collection efficiencies were calculated based on the parameterization for spheres (Beard and Grover, 1974).

Prodi et al. (1981) investigated the collection efficiencies of planar crystals in the laboratory. Their work suggests that dendritic and stellar crystals have higher collection efficiencies than plate crystals with the same Stokes number. They also suggested that plate crystals begin to collect droplets at lower Stokes numbers than indicated by the Pitter and Pruppacher (1974) calculations (although collection efficiencies are extremely low, ≈0.01). It is not appropriate to use the Prodi et al. data in this analysis because the Reynolds numbers in their laboratory study were much higher than those for our modeled particles. The discrepancies noted between the Pitter and Pruppacher and Prodi et al. studies suggest, however, that the collection efficiencies employed in this study should be regarded as approximations.

Terminal velocities were determined in the same manner as described by Heymsfield (1982). The density of the accreted rime was calculated from Heymsfield and Pflaum (1985) in a manner similar to the formulation given by Pflaum and Pruppacher (1979).

4. Numerical Simulation

A modeling study of the growth rates of ice crystals, compared to data obtained by previous studies, is presented in this section. The growth rates of isometric and double-plate crystals into graupel particles and subsequent precipitation particles are compared to the growth rates of crystals nucleated outside the $-9\degree$ to $-12\degree$C temperature range.

a. Model comparisons

The crystal masses predicted by the model at 140 s for diffusional growth at 1000 mb, and for ice crystals nucleated at different temperatures are displayed in Fig. 14. Similar results obtained in laboratory studies by Ryan et al. (1976) at 150 s, Fukuta (1980) at 140 s, and from a modeling study by Miller and Young (1979) at 120 s, are included for comparison in Fig. 14. The model's predictions of crystal mass compare well with those of the previous studies, again showing a peak in masses at $-6\degree$ and $-15\degree$C. The higher masses predicted in the $-9\degree$ to $-12\degree$C region in the present study, as compared to Miller and Young, can be attributed primarily to the modified shape factor assigned to the ice crystals nucleated in this region. This will result in enhanced diffusional growth of the crystals due to their isometrical or double-plate structure.

The growth rates of ice crystals at 500 mb, where most of the measurements in the present study were collected, are greater than those at 1000 mb due to enhanced diffusion of water vapor to the crystals at 500 mb. The reason is that the diffusivity of water vapor in air is inversely proportional to the atmospheric pressure (Hall and Pruppacher, 1976). This difference is
demonstrated in Fig. 15, where the dimensions along the $a$ and $c$ axes calculated in the model after 150 s at 500 and 1000 mb are compared with the results obtained by Ryan et al. (1976) after 150 s of growth at 1000 mb in their laboratory studies. Excellent agreement exists between the present model and the laboratory results obtained by Ryan et al. for growth at 1000 mb. The model calculations indicate larger crystal dimensions at 500 mb due to enhanced diffusional growth.

The average linear growth rate along the maximum dimension at 500 mb divided by that at 1000 mb over a period of 1200 s, was found to be approximately 1.32 ($\pm 0.27$) for temperatures between $-6^\circ$ and $-16^\circ$C. This value can be interpreted as the average growth enhancement of the crystals at 500 mb as compared to growth at 1000 mb. However, the critical diameter needed for the onset of accretion at 500 mb is a factor of 1.41 higher than that at 1000 mb due to the critical diameter being a function of the terminal velocity, which again is a function of the pressure (Heymsfield, 1972). Because of these offsetting factors, the time required to reach the critical diameter for accretion to begin at 500 mb is approximately equal to the time it takes at 1000 mb.

The temperature level at which the ice crystal starts to accrete liquid water, the time from nucleation to the onset of accretion, and the onset sizes for accretion were calculated by the model for crystals nucleated at six different temperature levels with an initial major axis dimension of 10 $\mu$m and spherical symmetry. The data are presented in Table 1 for an updraft of 1 m s$^{-1}$ and Table 2 for an updraft of 3 m s$^{-1}$. These vertical velocities are typical of those found in the studied clouds. The environmental sounding from 26 February 1985 was used in the calculations. The cloud base temperature was $+12.9^\circ$C at a pressure level of 733 mb. The average droplet size spectrum measured for the clouds (concentration of 1000 cm$^{-3}$, mean volume diameter of 14 $\mu$m, dispersion coefficient of 0.4) was used. Showers producing light rain developed on this day from clouds which had tops warmer than $-20^\circ$C (380 mb level). Crystals were simulated to rise in the updraft while growing by diffusion. The initial growth habit was determined by the temperature at the level of the crystal and the growth along $a$- and $c$-axes was determined according to the crystal's temperature at any moment.

The modeled onset diameters agree well with those found by the observations, presented in Figs. 8 and 11, reported by Ono (1969), Harimaya (1975), and Reinking (1979). The smallest crystal diameters for the onset of accretion are for particles nucleated at temperatures between $-8^\circ$ and $-10^\circ$C in an updraft of 1 m s$^{-1}$, and at temperatures warmer than $-12^\circ$C for an updraft of $70$ $\mu$m.

![Fig. 15. Comparison of the variation of crystal axial dimensions with temperature after 150 s of growth between the results obtained by Ryan et al. (1976) at a constant pressure of 1000 mb and the present modeling study at 1000 and 500 mb.](image)

**Table 1.** Model results of rime-ting characteristics for ice crystals nucleated at different temperature levels in a 1 m s$^{-1}$ updraft with a cloud droplet concentration of 1000 cm$^{-3}$, mean volume diameter of 14 $\mu$m, and dispersion coefficient of 0.4.

<table>
<thead>
<tr>
<th>Nucleation temperature (C)</th>
<th>Onset temperature (C)</th>
<th>Onset time (min)</th>
<th>Major axis ($\mu$m)</th>
<th>Minor axis ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-6^\circ$</td>
<td>$-7.4^\circ$</td>
<td>4.5</td>
<td>280</td>
<td>70</td>
</tr>
<tr>
<td>$-8^\circ$</td>
<td>$-9.4^\circ$</td>
<td>3.25</td>
<td>110</td>
<td>70</td>
</tr>
<tr>
<td>$-10^\circ$</td>
<td>$-11.4^\circ$</td>
<td>4.75</td>
<td>120</td>
<td>70</td>
</tr>
<tr>
<td>$-12^\circ$</td>
<td>$-13.4^\circ$</td>
<td>4.25</td>
<td>210</td>
<td>40</td>
</tr>
<tr>
<td>$-14^\circ$</td>
<td>$-15.4^\circ$</td>
<td>3.0</td>
<td>370</td>
<td>20</td>
</tr>
<tr>
<td>$-16^\circ$</td>
<td>$-16.9^\circ$</td>
<td>2.5</td>
<td>440</td>
<td>20</td>
</tr>
</tbody>
</table>

**Table 2.** Model results of rime-ting characteristics for ice crystals nucleated at different temperature levels in a 3 m s$^{-1}$ updraft with a cloud droplet concentration of 1000 cm$^{-3}$, mean volume diameter of 14 $\mu$m, and dispersion coefficient of 0.4.

<table>
<thead>
<tr>
<th>Nucleation temperature (C)</th>
<th>Onset temperature (C)</th>
<th>Onset time (min)</th>
<th>Major axis ($\mu$m)</th>
<th>Minor axis ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-6^\circ$</td>
<td>$-9.7^\circ$</td>
<td>3.75</td>
<td>140</td>
<td>70</td>
</tr>
<tr>
<td>$-8^\circ$</td>
<td>$-13.3^\circ$</td>
<td>7.0</td>
<td>160</td>
<td>70</td>
</tr>
<tr>
<td>$-10^\circ$</td>
<td>$-14.8^\circ$</td>
<td>4.5</td>
<td>190</td>
<td>50</td>
</tr>
<tr>
<td>$-12^\circ$</td>
<td>$-15.8^\circ$</td>
<td>3.5</td>
<td>250</td>
<td>30</td>
</tr>
<tr>
<td>$-14^\circ$</td>
<td>$-16.8^\circ$</td>
<td>2.5</td>
<td>415</td>
<td>20</td>
</tr>
<tr>
<td>$-16^\circ$</td>
<td>$-19.8^\circ$</td>
<td>3.25</td>
<td>430</td>
<td>20</td>
</tr>
</tbody>
</table>
3 m s\(^{-1}\). The colder onset temperature level for crystals nucleated at \(-8^\circ\mathrm{C}\) in a 3 m s\(^{-1}\) updraft is because the crystals (originally columns) are carried up through the \(-10^\circ\mathrm{C}\) to \(-12^\circ\mathrm{C}\) level (diffusional growth primarily along the prism face) before riming could begin. However, crystals nucleated at temperatures warmer than \(-9^\circ\mathrm{C}\) in nature tend to develop into capped columns as they rise through the \(-10^\circ\mathrm{C}\) level. The development of capped-columnar crystals is not considered in the present model and the crystal is rather viewed as a thick plate (see Tables 1 and 2). This will suppress the linear growth rate along the prism faces at temperatures below \(-10^\circ\mathrm{C}\) because the accumulated mass is evenly distributed over the prism faces. Nevertheless, its mass is probably about the same as that for the capped column.

It can be seen in Tables 1 and 2 that the time from nucleation to the onset of accretion is smallest for particles experiencing growth in the \(-14^\circ\mathrm{C}\) to \(-16^\circ\mathrm{C}\) region. A recent study by Takahashi (1986) of crystal riming in a vertical wind tunnel at temperatures between \(-14^\circ\mathrm{C}\) and \(-16^\circ\mathrm{C}\), with a pressure of 1000 mb, a liquid water content of 0.5 g m\(^{-3}\), and a mean volume diameter of about 12 \(\mu\mathrm{m}\), indicates that dendritic crystals begin to rim at 0.5 mm. Since the onset size for accretion is probably about the same at 500 mb as it is at 1000 mb, calculated onset sizes for accretion in this temperature range may be underestimated. The smaller onset sizes needed for crystals growing in the \(-10^\circ\mathrm{C}\) to \(-12^\circ\mathrm{C}\) region result in only slightly longer times needed for riming to begin.

b. Detailed case study of graupel development

To determine the contribution of crystals growing in the \(-9^\circ\mathrm{C}\) to \(-12^\circ\mathrm{C}\) temperature regime to the graupel and final precipitation development in clouds, it is necessary to compare their growth characteristics with crystals growing at other temperatures. Therefore, crystals were initialized in the model at six different temperature levels (\(-6^\circ\mathrm{C}, -8^\circ\mathrm{C}, -10^\circ\mathrm{C}, -12^\circ\mathrm{C}, -14^\circ\mathrm{C}, \) and \(-16^\circ\mathrm{C}\)) and were simulated to move in updraft speeds between 1 and 5 m s\(^{-1}\). The temperatures and vertical velocities used in the model runs were typical values for the early growth stages of summertime cumulus congestus clouds in the Highveld region of South Africa. Particles were simulated to grow at a constant pressure of 500 mb, with a cloud droplet concentration of 1000 cm\(^{-3}\), a dispersion coefficient of 0.4, and a mean volume diameter of about 14 \(\mu\mathrm{m}\). A constant liquid water content of 1 g m\(^{-3}\) was specified for the model runs to facilitate the comparisons, and since it is a typical value for the studied clouds.

Particles were “nucleated” with an initial major axis dimension of 10 \(\mu\mathrm{m}\) at the various temperatures and were simulated to grow in the updraft by diffusion and accretion over a 20 min period. From these runs, the time needed for the ice crystal to develop into a “spherical graupel particle” having the same mass as a sphere of 1 mm, with a density of 0.25 g cm\(^{-3}\) was determined for each of the initialized particles.

In nature, a convective cloud which reaches a temperature of, for example, \(-15^\circ\mathrm{C}\), typically grows upward through the \(-6^\circ\mathrm{C}\) level. As the cloud top decreases to temperatures below \(-6^\circ\mathrm{C}\), ice crystals may be nucleated which in turn will grow in the updraft. Thus ice particles nucleated at the warmer temperatures will have a time advantage over particles nucleated at colder temperatures due to the time it takes the air parcel, and thus the cloud top, to move from the warmer to the colder temperature level. To calculate this advantage in growth in the model, the time required for the parcel to rise from \(-6^\circ\mathrm{C}\) to the other temperature levels at which particles were nucleated (“offset time”) was added to the growth time of the nucleated particles. This offset time is especially important in cumulus congestus clouds which have relatively short lifetimes (Cooper and Lawson, 1984). A temperature lapse rate of 8\(^\circ\mathrm{C}\) km\(^{-1}\) was assumed for this purpose. If the in-cloud temperature lapse rate is less than 8\(^\circ\mathrm{C}\) km\(^{-1}\), the offset times will be greater, giving greater growth advantage to the crystals nucleated at the warmer temperatures. With the offset time not taken into account, the a priori assumption is made that the cloud already exists at all temperature levels, with the cloud top at temperatures colder than \(-16^\circ\mathrm{C}\). Consequently, crystals are nucleated simultaneously at the different temperature levels. This study, however, considers the clouds during their early growth stages with the cloud top growing through the \(-6^\circ\mathrm{C}\) level. For these clouds the offset time is of primary importance to determine the time needed for development of the first precipitation-sized particles.

The results of the model runs for updrafts of both 1 and 3 m s\(^{-1}\), with and without offset time, are presented in Fig. 16. The curves representing the crystal growth in a 1 m s\(^{-1}\) updraft clearly indicate that with no offset time (curve 2), ice crystals growing near the \(-15^\circ\mathrm{C}\) level—where the peak in diffusional growth occurs—become millimeter-sized graupel earlier than crystals nucleated at warmer temperatures. However, as discussed in section 4a, estimates of the accretion of dendritic crystals may be overestimated in the present model. It can be seen in Fig. 16 that with no offset time included in curve 2, the time needed for a nucleated crystal to grow to a millimeter-sized graupel particle, in a 1 m s\(^{-1}\) updraft, steadily decreases from \(-6^\circ\mathrm{C}\) to \(-16^\circ\mathrm{C}\).

When the offset time is included (curve 1), the situation changes considerably: crystals nucleated at warmer temperatures become the first graupel particles and crystals nucleated at successively colder temperatures need increasingly longer times to become graupel particles because it takes longer for the parcel to reach the colder temperatures. With offset time included (curve 1), it takes an ice particle nucleated at \(-6^\circ\mathrm{C}\)
between 15 and 16 min to reach 1 mm diameter, while the corresponding total time for an ice particle first nucleated at \(-14^\circ\)C is between 27 and 28 min. The curves (3 and 4) for a 3 m s\(^{-1}\) updraft in Fig. 16 show marked differences from the curves for a 1 m s\(^{-1}\) updraft. The difference in growth time between curves 1 and 2 (that is, with or without offset time added), increases from \(-4\) min at \(-8^\circ\)C to \(-20\) min at \(-16^\circ\)C, while that between curves 3 and 4 increases from 2 min at \(-8^\circ\)C to \(-7\) min at \(-16^\circ\)C. This result is a reflection of the decrease in the offset time as the updraft speed increases. The other marked difference is that with no offset time included, the time needed for an ice crystal to grow to a millimeter-sized graupel in a 3 m s\(^{-1}\) updraft (curve 4), is a maximum for particles nucleated at \(-8^\circ\)C and a minimum at \(-12^\circ\)C. This trend is also reflected in curve 3 with the offset time included. The maximum at \(-8^\circ\)C may be due to the lack of treatment of capped columns in the present model, with the particle growing slowly by diffusion only as it moves through the \(-9^\circ\) to \(-12^\circ\)C level, and starting to accrete liquid water only around the \(-15^\circ\)C level.

With the offset time included in both a 1 and 3 m s\(^{-1}\) updraft, crystals nucleated at the \(-6^\circ\)C level develop into graupel the fastest because they begin riming before reaching the \(-9^\circ\) to \(-12^\circ\)C region. A second minimum in the time required for growth to 1 mm graupel occurs for particles nucleated between \(-10^\circ\) and \(-12^\circ\)C in a 3 m s\(^{-1}\) updraft. A maximum occurs for particles nucleated at \(-16^\circ\)C, with a secondary peak at \(-8^\circ\)C, in a 3 m s\(^{-1}\) updraft, for reasons previously discussed. In model runs with updraft speeds higher than 3 m s\(^{-1}\), growth times were similar to those in curves 3 and 4. At the higher speeds, however, especially for particles nucleated at temperatures colder than \(-10^\circ\)C, particles were carried to temperatures below \(-20^\circ\)C (above cloud top) before they grew to 1 mm graupel. Growth times for an updraft of 2 m s\(^{-1}\) were similar to those for an updraft of 1 m s\(^{-1}\). These results are supported by observations in the Bethlehem region (Krauss et al., 1986), where relatively small clouds (tops warmer than \(-20^\circ\)C) with weak updrafts were able to produce graupel particles rather efficiently when cloud lifetimes at the \(-10^\circ\)C level were on the order of 20 min.

The total mass of ice crystals nucleated at different temperature levels was also calculated in the model runs. The crystals were calculated to grow by diffusion and accretion for 20 min. With no offset time (Fig. 17a), crystals nucleated at temperatures colder than \(-12^\circ\)C attained the highest mass growth rates (possibly overestimated), while particles nucleated around \(-6^\circ\)C attained the lowest mass growth rates. With offset time included (Fig. 17b), the crystals nucleated at the warmer temperatures attained higher masses faster than those at lower temperatures.

Similar results were obtained for an updraft of 3 m s\(^{-1}\). When no offset time was included (Fig. 18a), crystals nucleated between the \(-10^\circ\) and \(-12^\circ\)C level attained the highest mass growth rates, while crystals nucleated at \(-8^\circ\) and \(-16^\circ\)C attained the lowest mass growth rates. With offset time included (Fig. 18b), particles nucleated at \(-6^\circ\)C attained a certain mass before any of the particles nucleated at any other temperature level, although particles nucleated between \(-10^\circ\) and \(-12^\circ\)C attained the same mass only 2 to 3 min later. The lowest growth rate, and thus the smallest mass, was attained by crystals nucleated at \(-16^\circ\)C; particles nucleated at \(-8^\circ\) and \(-14^\circ\)C attained the same mass as crystals nucleated at \(-6^\circ\)C, but 4 to 7 min later.

The time taken for an ice particle to grow to a graupel particle is of critical importance in the development of precipitation. Our model calculations suggest that ice crystals nucleated near \(-6^\circ\)C can be efficient graupel embryos in weak updraft situations. The measurements in clouds described in section 2, however, generally do not support these findings since natural ice is not observed until cloud tops reach the \(-9^\circ\) to \(-12^\circ\)C region. This is primarily due to a lack of natural ice nuclei that are active at temperatures warmer than \(-8^\circ\)C. The model indicates, however, that in actively growing clouds (updrafts > 3 m s\(^{-1}\)), crystals nucleated between \(-10^\circ\) and \(-12^\circ\)C may produce graupel particles nearly as fast as crystals nucleated near \(-6^\circ\)C, and consistently faster than crystals nucleated at other temperatures.

The treatment of capped columns (columns with end plates) is not considered in the present model; such
6. Summary

Ice crystal data collected within South African summertime continental cumulus congestus clouds, coupled with a modeling study, have revealed the following findings:

1) The first detectable ice nucleates between the $-9^\circ$ and $-12^\circ$C levels as the cloud top rises through these levels. First-ice measurements indicate that 90% are

Fig. 17. Particle mass as a function of time for crystals nucleated at $-6^\circ$, $-8^\circ$, $-10^\circ$, $-12^\circ$, $-14^\circ$ and $-16^\circ$C in a 1 m s$^{-1}$ updraft with (a) no offset time included and with (b) offset time added.

Particles thicken uniformly throughout their length. This may lead to an underestimate of the riming threshold for these particles, especially in view of previous studies (Ono, 1969; Reinking, 1979) which indicate that capped columns are very efficient rimers. Thus, the time needed for ice crystals nucleated at $-8^\circ$C to develop into graupel particles in growing convective clouds, may be largely overestimated.

Fig. 18. Particle mass as a function of time for crystals nucleated at $-6^\circ$, $-8^\circ$, $-10^\circ$, $-12^\circ$, $-14^\circ$ and $-16^\circ$C in a 3 m s$^{-1}$ updraft with (a) no offset time included and with (b) offset time added.
double-plate crystals, while columns and single plates comprise <10%. A frozen drop center was observed in about 30% of the double-plates analyzed. The two plates of a double-plate ice crystal usually grow simultaneously up to a certain diameter (200 to 300 μm), whereupon growth is preferentially along one crystal, although symmetric growth can also occur.

2) In situ ice crystal measurements in the temperature range −5°C to −15°C give new information on axial dimensions for crystal diameters up to 500 μm, and bulk densities for crystal diameters up to 200 μm for isometric and double-plate ice crystals. Generally, axial ratios decrease with increasing crystal diameter. When the air gap between crystals is included and the crystal is treated as a thick plate, excellent agreement exists between previous laboratory studies and the present field observations. The present study also suggests that the axial ratios and bulk densities are nearly independent of atmospheric pressure.

3) The basal-plane area of double-plate crystals with sector-like branches is a function of crystal diameter. The approximate relation between the basal plane area \((A)\) in square millimeters and the crystal diameter \((D)\) in millimeters was calculated to be \(A = 0.36D^{1.7}\).

4) Isometric and double-plate ice crystals start to accrete liquid water at smaller sizes than single plates, dendrites, or needle crystals, supporting the conclusions of Fukuta et al. (1982) that riming growth is most efficient for crystals nucleating and developing near the −10°C level. The onset size for riming of isometric and double-plate ice crystals was found to be between 80 and 150 μm, with heavily rimed crystals first observed in the size range 150 to 200 μm. In a similar analysis, the onset size of riming on hexagonal plates with sector-like branches was found to be between 250 and 300 μm, which compares favorably with the values obtained by Ono (1969), Harimaya (1975) and Reinking (1979).

5) The predicted crystal masses obtained after 140 s of diffusional growth for temperatures between −2°C and −20°C were compared with those obtained by Ryan et al. (1976), Miller and Young (1979) and Fukuta (1980). In general, the crystal masses predicted by the present model compare well with the other studies, although crystal masses in the −9°C to −12°C region are larger in the present model due to a modified shape factor which enhances diffusional growth. A modified axial ratio was used in the −10°C to −12°C region to account for the air gap in double-plate crystals.

6) The model-predicted linear growth rates along the maximum dimension at 500 mb are approximately a factor of 1.32 larger than those predicted at 1000 mb. However, for precipitation development via the riming process, this growth enhancement factor is offset by the larger critical ice crystal diameter needed for the onset of riming at 500 mb, indicating that times for riming onset are about the same at all pressures (altitudes).

7) The predicted crystal diameters for the onset of accretion (Tables 1 and 2) for crystals nucleated at six different temperature levels and carried in updrafts of 1 and 3 m s⁻¹ compare well with observations (Figs. 8 and 11). The time needed for ice crystals to nucleate at each temperature level and grow to sizes at which they start accreting liquid water also compares well with observations in clouds.

8) Comparisons between the growth characteristics of ice crystals nucleated at different temperature levels and carried in updrafts of 1 and 3 m s⁻¹, with and without offset time added, revealed the following:

(i) In a 1 m s⁻¹ updraft, with the offset time added, crystals nucleated at −6°C are the first graupel embryos, and crystals nucleated at colder temperatures require increasingly longer times to grow to millimeter-sized graupel particles. Without the offset time included, the trend is reversed, with crystals nucleated at −16°C becoming graupel particles in the shortest times.

(ii) The particle growth offset time decreases as the updraft speed increases. Consequently, in a 1 m s⁻¹ (3 m s⁻¹) updraft, an ice crystal nucleated at −6°C experiences 20.8 min (6.9 min) of growth before reaching the −16°C level. With no offset time included, and a 3 m s⁻¹ updraft, the time to reach millimeter-sized graupel particles is a minimum for particles nucleated between the −10°C and −12°C levels because particles are carried up into the region where the peak in diffusional growth occurs. With offset time included in a 3 m s⁻¹ updraft, the time it takes to reach millimeter-sized graupel particles is a minimum for particles nucleated at −6°C, −10°C, and −12°C, and a maximum for particles nucleated at −16°C.

9) The calculations presented here are based on theoretical collection efficiencies and thus should be regarded as broad approximations. Nevertheless, the calculations with offset time included indicate that particles nucleated at the warmer temperatures (> −12°C) in clouds are the only ones which can develop into 1-mm graupel within cloud lifetimes < 20 min and thus are of critical importance to the development of precipitation within continental cumulus clouds.

10) Ice crystals nucleated at temperatures warmer than −9°C and growing in an updraft tend to develop into capped columns as they rise through the −10°C level. The development of these crystals is, however, not considered in the present model; they are rather viewed as thick plates. This assumption suppresses the linear growth rate of the end plates although crystal mass is probably fairly accurately derived. This may lead to an underestimate of the riming ability for these particles, especially in view of the findings in previous studies (Ono, 1969; Reinking, 1979) that capped columns are very efficient rimers. Additional measurements and modeling improvements are required in these areas.
7. Conclusions

This study has revealed that within South African summertime continental cumulus congestus clouds, the first ice crystals nucleate between $-9^\circ$ and $-12^\circ$C, and that 90% of these crystals develop a double-plate structure. These crystals begin to accrete liquid water at sizes considerably smaller than previously thought. Using the measured physical characteristics of these particles (e.g., axial ratio and bulk density), a modeling study revealed that these crystals are very efficient graupel embryos.

The introduction of “offset time” in this paper presents a more realistic approach to model precipitation growth in convective clouds. Future investigations of precipitation development in cumulus congestus clouds should include this concept.

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