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THE DENSITY AND STRUCTURE OF HAILSTONES

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K. A. Browning, F. H. Ludlam
and W. C. Macklin

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K. A. Browning, F. H. Ludlam, and W. C. Macklin[1]

CONTENTS

[1] Now at Department of Physics, University of Western Australia.

Summary

Macklin's (1962) experimental study of ice accretions and estimates of the typical conditions in the cumulonimbus of cold air masses and of summer continental air masses are used to deduce the density of ice in the hailstones produced by these clouds. It is shown that generally small hail has a low density; it may reach the ground in the cold air masses but melts into rain in summer conditions. Large hail may have a low density core if grown upon a small frozen cloud droplet, but otherwise always has a high density. The presence of alternate layers of cloudy and clear ice is attributed to transitions between dry and wet growth. Large hailstones can be grown during a slow second ascent in a steady updraught whose speed increases with height. It is shown that under certain simplifying assumptions the conditions for such persistent growth imply that their surface temperatures are always close to $0^{\circ}C$, and therefore that minor fluctuations in cloud liquid water content may cause transitions. When the simplifications are removed this result cannot be demonstrated, but it seems reasonable that alternate layers of clear and opaque ice could be produced in a similar way, and need not indicate successive rises and falls in an intermittent updraught, as formerly thought.

Introduction

In cold weather "soft" hail falls from shower clouds. The particles are small (diameters up to several mm), and are easily compressed, having a low density. On the other hand in summer hail may be large (diameters up to several cm), has a high density, and is hard. Big stones may rebound several feet into the air from roads and paths. When cut open they are found to contain several layers of alternately clear and cloudy ice.

In this paper we try to explain these familiar properties on the basis of Macklin's (1962) experimental study of ice accretions, using estimates of the typical conditions in the supercooled parts of both cold- and warm-weather cumulonimbus.

I. Hail density

1. The character of the deposit on ice surfaces growing by accretion

Macklin examined the rime deposited from a supercooled cloud upon wind-swept rotating cylinders under a wide range of conditions: air temperature -5 to -30°C, air speed 2½ to 12 m sec^{-1}, cloud water concentration less than 1 to about 7 g m^{-3}, cloud droplet median volume radius, r, 11 to 32 microns, and cylinder diameter 1 to 14 mm.

The rime density was found to be a function of (rv_o/T_s), where v_o is the droplet impact speed (somewhat less than the air speed V) and T_s is the depression below 0°C of the temperature of the rime surface (raised above the air temperature by the release of the latent heat of fusion). The form of the relation is shown in fig.1.

At high rates of accretion the rime surface temperature approached 0°C. At surface temperatures above about -5°C collected droplets fused before completely freezing, so that the deposit became a 'glaze' rather than a rime. Opacity and whiteness in such ice is due to the presence of minute bubbles of air which previously was dissolved in the droplets.

When a certain rate of accretion was exceeded the surface temperature became 0°C and not all of the collected water froze. In general the excess did not drip from the cylinder as anticipated (Ludlam, 1958), but was retained in a 'spongy' layer (Macklin, 1961). The wet surface could also accrete ice particles present in the air stream, but unless they were abundant the ice deposited beneath a liquid film was found to be transparent (containing few although perhaps rather large air bubbles) or quite clear. Presumably air coming out of solution was able to diffuse away, whereas at lower surface temperatures droplets froze individually and from their surfaces inwards, trapping air coming out of solution in their interiors.

2. The density of hail

Measurements[1] of the density of soft hail from cold-weather showers vary from about 0.04 to 0.2 g cm^{-3}. List (1958) gives a density of 0.5 to 0.7 g cm^{-3} for particles of diameter up to 6 mm collected from summer showers at the Weissfluhjoch Observatory (2,665 m above sea level); large hailstones have a mean density close to that of pure ice[2].

One reason for the comparatively high density of hail grown in warm-weather clouds seems to be that in their supercooled parts (usually well above the cloud base, in the upper troposphere), the parameters r, v_0 and T_s, for a particle of given size, all change in a manner to increase significantly the term (rv_0/T_s). The higher temperature at the cloud base tends to raise the concentration of liquid water in the supercooled zone, and hence to increase r and decrease T_s. The lower air density tends to increase the fall-speed, and this, with the rise in r, appreciably increases v_0.

If in a model cloud air pressure, temperature and vertical speed, together with the droplet mean-volume radius and the liquid water concentration, are specified as a function only of height, then the rate and density of rime deposition can be calculated throughout the growth of a hailstone introduced as an embryo at some appropriate level.

Nakaya and Terada measured the size and fall-speed of soft hail particles which fell on a mountain at an air pressure of about 900 mb (probably a few hundred metres above the cloud base) and at temperatures between -8 and -15°C. In order to obtain calculated results comparable with their measurements and

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[1] Nakaya and Terada (1935) : 0.04 to 0.24 g cm^{-3} for particles of diameter 1 to 4 mm. Magono (1954) : 0.04 to 0.17 g cm^{-3} for diameters of 1 to 6 mm. Arenberg (1941) : 0.2 g cm^{-3} or less. Ludlam (1952) : about 0.1 g cm^{-3} for particles of diameter 1 mm.

[2] Vittori and Di Caporiacco (1959); Macklin, Strauch and Ludlam (1960).

appropriate in general to clouds produced by convection in polar air masses, we have first taken a model cloud whose base has a pressure of 900 mb and a temperature of 0°C. In this cloud the adiabatic liquid water concentration W is 1.8, 2.5 and 2.7 g m^{-3} where the cloud temperature is respectively -10, -20 and -30°C (at heights of about 2.4, 3.7 and 4.9 km). We have assumed that in such a cloud the average (median volume) cloud droplet radius r is 10 microns, and have calculated the surface temperature of hail of various sizes growing by accretion at the air temperatures mentioned, from which we have obtained the density of the deposited ice.

For comparison we have calculated the same quantities in a model cloud representative of summer hail-clouds, whose base at 900 mb has a temperature of 20°C and whose liquid water concentration in the supercooled zone is taken to be everywhere 6 g m^{-3}, close to the adiabatic values which vary between 6.1 and and 6.7 g m^{-3}; in the supercooled zone of this cloud an average droplet radius r of 15 microns is assumed.

The density of the accreted ice depends upon r, v_0 and T_s (fig.1). The impact speed v_0 of the accreted droplets is generally 80 to 90% of V, the hailstone fall-speed, in the range of conditions considered, and has therefore been replaced by V without introducing significant error. The values of T_s were calculated following the treatment of the heat economy outlined by Ludlam (1958)[1], and involved deriving the efficiency of catch E of the accreting hailstones. This was obtained as a function of Reynolds number and a parameter k using the formulae of Langmuir and Blodgett (1946); k depends mainly upon the fall-speed V, which was calculated as a function of stone size and mean density

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[1] As in that treatment, convection coefficients a, b = 1 + 0.3 $(Re)^{\frac{1}{2}}$ were further simplified to a, b = 0.3 $(Re)^{\frac{1}{2}}$. This eased the work at the cost of introducing errors at smaller Reynolds numbers and causing a slight overestimate of T_s and underestimate of density for small particles (diameter < ½ mm).

at each level in the warm-base cloud (using drag coefficients appropriate to spheres), and for the 4 km level in the cold-base cloud.

Without going to the extent of assuming particular updraught profiles and calculating the density of the accreted ice throughout the whole history of growth of individual hailstones, we can draw some useful conclusions simply by considering how the density changes with hailstone size at a given air temperature. Accordingly, we calculated for temperatures of -10, -20 and -30°C the density of ice accreted by stones of various sizes and mean density[1], and hence the rate of change of mean density as a function of size. On a diagram of mean density against diameter isopleths of this rate of change can be drawn, and thereby a whole series of curves which show how the mean density changes if growth progresses at the given temperature from any chosen initial size and density. From several such diagrams we have extracted the curves of figs. 2 and 3, which refer to an initial density of 0.9 g cm^{-3} and initial diameters of 200 microns, 1 mm and 2 mm, such as might be produced by the freezing of drops of about these sizes (i.e., large cloud droplets, small raindrops and ordinary raindrops).

Considering first the growth in the cold-base cloud, it is interesting that although hailstones with diameters of several mm may be a few degrees Celsius warmer than their environment, their equilibrium surface temperature never reaches 0°C while they are in the supercooled zone: the rate of accretion is everywhere insufficient for this, the concentration of cloud water approaching zero where the air temperature rises towards 0°C. Consequently in this cloud model the history of hailstones which reach these sizes is similar, apart from their variable density, to that of raindrops

[1] In the absence of any experimental data it has been assumed that the density of the accreted ice was 0.06 g cm^{-3} at all values of (rv_0/T_s) below 0.5.

growing by coalescence, already examined by Ludlam (1951) and others. In particular, when the updraught speed does not vary substantially, or increases with height, the bulk of the growth is accomplished near the top of the particle trajectories. In layers nearer the cloud base the cloud water concentration is lower; moreover the speed relative to the ground of the particles is greater, so that they pass rapidly upwards through these layers while they are small and rapidly downwards during their fall from the cloud. Accordingly, in the cold-base cloud the bulk of the growth can be regarded as occurring at temperatures of -10°C or less. Fig. 2 then implies that low density hail is not necessarily grown on ice crystals, since the growth of droplets of all sizes after freezing is at first accompanied by a very rapid decrease in mean density. The freezing of cloud droplets produces hail of 2-3 mm diameter which has a mean density of less than 0.1 to about 0.3 g cm^{-3}, practically independently of the path in the cloud, in conformity with the Japanese observations. Even rather larger hail (diameter 3-6 mm) can be expected to have a mean density of less than 0.6 g cm^{-3}, and therefore to be easily compressible, as observed. Hailstones of this size and density have fall-speeds of 10-15 m sec^{-1} and are about the largest which are likely to be produced in polar air masses, in which the instability and hence probably the cloud updraught speeds are rather small (Ludlam and Scorer, 1953). If larger stones are produced their mean density must approach the higher values characteristic of summer hail. In the interior of continents even in summer hail-clouds may have bases which are cold because of their rather high level (3 to 4 km above ground), but unlike the cold-base clouds of the polar air masses they may contain updraughts sufficiently strong to permit the growth of large hailstones. In the polar air masses hail of all sizes is often likely to reach the ground without melting, since the wet-bulb temperature exceeds 0°C only very near the surface, even outside the downdraughts which may accompany precipitation.

Fig.3 shows that the mean density of a hailstone grown from an embryo of a certain size is greater in the warm-base cloud, but that if the embryo is a small frozen cloud droplet the density should be low (and the ice opaque) in a core at least 1 or 2 mm across. Sometimes (Macklin, Strauch and Ludlam, 1960) hailstones are found to have central parts several mm across consisting of clear ice with no trace of such an opaque core, suggesting that the embryo could have been a raindrop of diameter 1 to 2 mm or more which froze and commenced growth as a hailstone at a temperature above about -20°C. This drop could have grown by the coalescence of cloud droplets, or it could have been produced by the melting of a low-density hailstone which re-entered the updraught well below the 0°C level (were it to re-enter above this level and straightway enter the wet-growth regime, the first layer of glaze to be deposited would probably seal the interior against the inward percolation of excess surface liquid).

Irrespective of the size of the embryo, prolonged growth leading to the production of large hailstones of diameter 1 cm or more inevitably leads to high mean densities. Considering that hailstones of diameter less than 1 cm melt completely before reaching the ground in warm weather (0°C level 4 to 5 km above the ground; see Ludlam, 1958), it is reasonable that the hailstones of summer storms are found to have a mean density close to that of pure ice.

II. The growth and structure of large hail

1. The growth of large hail

Large hailstones have fall-speeds of 30 m sec^{-1} or more, and in any theory their production requires that the updraughts in which they are grown shall have closely comparable speeds. In the early stages of its growth ($V < 10$ m sec^{-1}) the fall-speed of an embryo hailstone increases rather slowly, and a steady strong updraught carries it through the supercooled zone of a cloud (between the 0°C and -40°C levels) before it attains a large size (Ludlam, 1958). Consequently some way must be found of having it re-enter this zone. For example, if the updraught is intermittent it may repeatedly be let fall from a high level and then be carried up again. This might happen if the updraught were provided by a succession of thermals, and seems consistent with the striking characteristic of many big hailstones, the presence of shells of alternately clear and cloudy ice, which it has been surmised may be deposited respectively near the base and near the top of the zone of supercooling.

Recently Browning and Ludlam (1962) have suggested that a severe hailstorm may contain an almost steady updraught which enters and leaves the storm almost horizontally on the same side, so that hailstones may fall from a high level and re-enter the updraught. Further, there is some evidence that in such a storm a substantial proportion of the updraught ascends practically adiabatically, with a speed which increases roughly linearly with height to reach a maximum of some tens of m sec^{-1} near the tropopause. In these circumstances an embryo hailstone which re-enters the updraught at a low level may be lifted slowly through the supercooled zone, both its fall-speed and the upward speed of the surrounding air increasing at about the same pace as it rises, so that it eventually attains a large size during only one further ascent. A growing hailstone has a surface temperature close to $0^{\circ}C$ near the $0^{\circ}C$ level when it is small, and also near the top of the supercooled zone when it is large (providing the liquid water concentration remains sufficiently high: Ludlam, 1950), and therefore perhaps throughout the second ascent. Then even in a steady updraught minor fluctuations in cloud water concentration might cause variations of surface temperature between $0^{\circ}C$ and a few degrees lower, and hence produce alternate layers of opaque ice and transparent ice[1]. A quantitative examination shows this not only to be possible but plausible.

We consider the growth of a hailstone of radius R which retains all the liquid accreted, even when the accretion rate somewhat exceeds the maximum rate of freezing.

Then

$$dR / dt = (EW) V / 4 \delta \qquad \ldots (1)$$

where V, the fall-speed of the hailstone in a particular cloud, can be regarded as a function of R and height z, and as always greatly exceeding that of the accreted droplets,

δ is the density of the accreted water, to be assumed as 0.9 g cm^{-3},

E is the collection efficiency, and

W is the liquid water concentration in the cloud air, usually regarded

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[1] Macklin (1960) found during an examination of sixty hailstones from one storm that the opaque layers contained multitudes of minute air bubbles and very small crystallites (volume $\lessdot 10^{-5}$ cm^3). Transparent layers contained comparatively fewer and larger bubbles, and much larger crystallites (volume 10^{-4} to 10^{-1} cm^3). The size of the large crystallites is consistent with the view that they were nucleated by small ice crystals or frozen droplets accreted while the surface was covered by a film of liquid. Sudden increases in the rate of accretion of ice particles sufficient to explain the abrupt transitions to the great concentrations of the small crystallites seem improbable; rather, it is supposed that a sudden small decrease in the rate of accretion of droplets lowers the surface temperature and freezes the surface film of liquid. Accreted droplets then commence to freeze on contact with the ice surface, and in general the disposition of the crystal axes is preserved in the new ice. However, it is surmised that the momentum of the droplets sometimes breaks or distorts the first-formed bonds with the rather irregular surface, and thereby causes the displacement of their axes and the development of fresh crystallites. Even though this might occur during only a small proportion of the impacts it could be responsible for the high concentration of crystallites observed to be associated with dry growth.

as a function only of z in a steady updraught. When the accreted droplets have radii exceeding 10 microns, as is likely in the upper parts of hail clouds, the value of E is close to unity, but because W also is not accurately known we prefer to associate these parameters and refer to an effective water concentration EW, or W'.

In the regime of Reynolds numbers with which we are concerned ($V > 10$ m sec^{-1}, $Re > 10^3$) hailstones which are spherical or nearly so have a drag coefficient c which has an approximately constant value of 0.6 (Macklin and Ludlam, 1961). Accordingly we may use as a fall-speed law

$$V^2 = 8gR\delta / 3\rho c \qquad \ldots (2)$$

where ρ is the air density. For the present we neglect the variation of air density about a mean value $\bar{\rho}$ in the zone of supercooling, which in summer weather lies between about the 4 km (temperature 0°C) and 9 km (temperature -40°C) levels. Large hailstones have a mean density close to 0.9 g cm^{-3}, often even in their centres, and we shall take this value also as a constant.

We assume that in the supercooled zone the updraught speed U increases steadily with height:

$$U = \alpha z \qquad \ldots (3)$$

and that W' is constant with height (and time), which is approximately true in adiabatic updraughts with high cloud base temperatures (Ludlam, 1950). Then we may easily obtain from (1), (2) and (3)

$$d(U-V)/dz = \alpha - gW'/3\bar{\rho}c(U-V) \qquad \ldots (4)$$

Thus under these conditions if (U - V) at the place where the embryo hailstone re-enters the updraught and resumes growth has the particular value $gW'/3\bar{\rho}c\alpha$, then the hailstone may ascend slowly and steadily at constant speed, the increase in its fall-speed keeping pace with that in the speed of the updraught encountered. In the warm-base cloud $\bar{\rho}$ is about 5×10^{-4} g cm^{-3} (corresponding to a temperature of -20°C and a pressure of about 360 mb), while in a hailstorm cloud α will be about 50 m sec^{-1}/10km, or 5×10^{-3} sec^{-1}; in these circumstances (U - V) in m sec^{-1} is about 2 W' when W' is expressed in g m^{-3}, and hence would usually amount to a few m sec^{-1}. Consequently near the -40°C level, where the growth must be presumed to cease, the hailstone will have a fall-speed very nearly equal to the updraught speed, and a size which during a second steady ascent through the supercooled zone has become practically the maximum which can be attained in the kind of updraught assumed. This mode of growth is not stable; if anywhere for some reason (U - V) falls a little below the equilibrium value the difference increases with height and the stone fails to reach the top of the supercooled zone, being precipitated with a smaller final size. If on the other hand the value of (U - V) exceeds the equilibrium value the difference again increases: the stone accelerates upwards and passes through the top of the supercooled zone, again with a smaller final size. By a second re-entry into the updraught at a higher level it might resume the optimum growth, but clearly the chances of this are likely to be very small. The stringency of the condition to be met by U and V at re-entry suggests a reason why the concentration of the largest stones is always observed to be extremely small.

It is more difficult to demonstrate the plausibility of this mode of growth when more realistically one considers that ρ and W' vary with height, and that the updraught speed at a given level decreases towards its borders, where the embryo hailstones re-enter. Nevertheless, it seems reasonable that an essentially similar mode of growth can occur.

2. The structure of large hail

The surface temperature T_s of a growing hailstone is raised above the environment temperature T by the release of latent heat of fusion. The heat economy has been examined by Ludlam (1958), who concludes that T_s just reaches 0^oC when the stone attains a size such that its fall-speed is given by

$$V^3 = 7.7g^8[(DL_v\Delta\rho - KT)/(L_f + T)]^2/c\eta W'^2 \qquad \ldots (5)$$

where L_v, L_f are respectively the latent heats of evaporation and fusion,

D is the coefficient of diffusion of water vapour in air and

K is the coefficient of thermal conductivity of air,

$\Delta\rho$ is the difference between the saturated vapour densities over water at 0^oC and at a temperature T,

η is the viscosity of the air, and

c is the drag coefficient of the hailstone.

On the occasion of the Wokingham hailstorm discussed by Browning and Ludlam (1962), the ascent of air occurred approximately along the saturated adiabatic corresponding to a wet-bulb potential temperature of 19^oC. For these conditions and for several values of W' between $\frac{1}{2}$ and 8 g m^{-3}, fig.4 shows as a function of height the values of V and R for which the hailstone surface temperature is just 0^oC. In this diagram hailstones in the wet-growth condition, in which clear or transparent ice is deposited, are represented by points lying to the right of the appropriate isopleth. (However, when the points lie far to the right of the isopleths, and if ice particles are accreted as well as excessive liquid, then spongy ice is formed which may not be transparent, and in any case will contain air bubbles if subsequently the surface temperature falls below 0^oC and internal freezing occurs.)

It will now be shown that when W' is a continuous function of height such that the value of V for which the surface temperature is just $0^{\circ}C$ increases with height (as will always be the case in adiabatic updraughts), there is a particular profile of U, the updraught speed, for which a hailstone growing during its second ascent has a surface temperature which is always just $0^{\circ}C$. It is assumed that the second ascent begins when the hailstone re-enters the updraught with a fall-speed V of about 10 m sec^{-1}.

We note that $V = f(R, \rho)$, so that

$$\frac{dV}{dz} = \frac{\partial V}{\partial R} \cdot \frac{dR}{dt} \cdot \frac{dt}{dz} + \frac{\partial V}{\partial \rho} \cdot \frac{d\rho}{dz}$$

From (2) $\qquad \dfrac{\partial V}{\partial R} = 4g\delta/3c\rho V$, and $\dfrac{\partial V}{\partial \rho} = -V/2\rho$

while from (1) $\qquad \dfrac{dR}{dt} = W'V/4\delta$

Thus $\qquad \dfrac{dV}{dz} = \dfrac{4g\delta}{3c\rho V} \cdot \dfrac{W'V}{4\delta} \cdot \dfrac{1}{U-V} - \dfrac{V}{2\rho} \cdot \dfrac{d\rho}{dz}$

whence $\qquad U-V = (W'g/3\rho c)/(\dfrac{dV}{dz} + V.\dfrac{1}{2\rho} \cdot \dfrac{d\rho}{dz}) \qquad \ldots (6),$

i.e. $\qquad U-V = f(V, z)$

If now for a given distribution of W' with height we select at every level that value V^* of V for which the hailstone has the surface temperature $0^{\circ}C$, we determine the form of the updraught U^* which ensures this condition:

$$U^*-V^* = (W'g/3\rho c)/(\frac{dV^*}{dz} + V^*.\frac{1}{2\rho} \cdot \frac{d\rho}{dz}) \qquad \ldots (7).$$

Fig.5 shows U^*-V^* as a function of V^* for given constant values of W', from which it can be seen that with the liquid water concentrations of 3-5 g m^{-3} which may be typical of the supercooled zones of warm-base clouds the differences between the updraught speed and the fall-speed of the constantly just-wet hailstone vary between about 5 and 10 m sec^{-1}, remarkably close to the 6 to 10 m sec^{-1} which according to our previous considerations is about the value required to ensure that a hailstone becomes large during its second ascent.

From the previous two figures we have derived fig.6, which for various values of W' shows U^* as a function of height. It appears that for values of W' in the typical range 3-5 g m^{-3} the distribution of U^* with height is practically the same. Evidently when hailstones of fall-speed 30 to 40 m sec^{-1} are produced during ascent to the top of the zone of supercooling the value of U at this level will always be close to the value of U^*. If also at lower levels the values of U were close to those of U^* (as has been shown to be probable for the largest stone when $\alpha \approx 5 \times 10^{-3}$ sec^{-1}) it would be reasonable to expect that throughout their second ascent the surface temperature of the stones would always have been very nearly 0°C, so that small changes in the cloud liquid-water concentration could have caused transitions between the wet- and the dry-growth regimes and the deposition of layers of alternately clear and cloudy ice. Such changes in cloud density need not necessarily imply corresponding changes in updraught speed. Wherever the updraught is even slightly tilted the stones traverse the streamlines and may encounter fluctuations due to an irregular distribution of humidity with height in the low-level layers of air which turn upward to compose the updraught.

Reference to the heat economy of a growing hailstone (Ludlam, 1958) shows that if only sensible heat were transferred to its environment then the elevation of its surface temperature above that of the air would be directly proportional to the effective cloud liquid water concentration W'. However, because some heat transfer is accomplished by evaporation from the surface a given fractional change in W' produces a rather smaller fractional change in the elevation of the surface temperature. In the warm-base clouds a 10% decrease in W' causes a fall of 8 to 6% in the elevation of surface temperature of a hailstone which is just wet at air temperatures between -5°C and -30°C, and hence a change of between about ½ and 2°C respectively. Especially at the lower air temperatures such a fall would be sufficient to change the appearance of the deposited ice from clear or transparent to opaque. If the hailstone were originally not just in the wet condition, that is, if the actual updraught profile does not very closely follow that of U^*, then the occurrence of transitions would demand greater variations in W'. Their production in the manner described may then seem less probable, and their prevalence in large stones to hint either at the old concept of an intermittent updraught or to some undiscovered process causing an oscillation about the wet-growth condition. However, we have given some reason to suppose that it is just the largest stones which have persistently grown close to this condition. Alternatively stated, the profiles of U and of U^* will always nearly coincide, at least in the upper part of the supercooled zone, if large hailstones are grown. Nearer the 0°C level the speed of the strong part of the updraught can be expected generally to exceed the few m sec^{-1} in the profile of U^*, but we must consider that during re-entry the embryo hailstones first encounter lesser speeds on the borders of the updraught. Thus it may arise that a proportion of the hailstones always experience an updraught which closely conforms with U^* throughout the whole of their second ascent.

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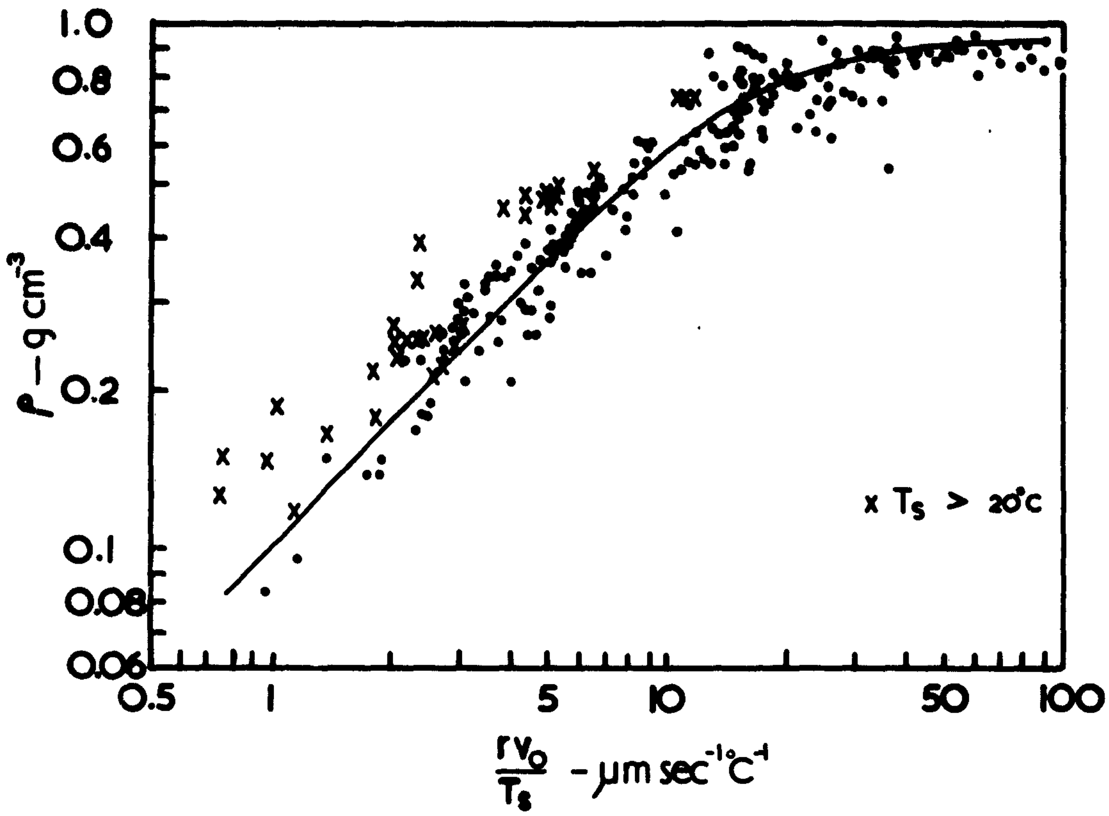

Fig. 1. The density of rime ice as a function of the parameter (rv_0/T_s), where r is the median volume radius of the cloud droplets (in microns), v_0 is their impact speed ($m\ sec^{-1}$) and T_s is the depression below 0°C of the rime surface temperature - after Macklin (1962).

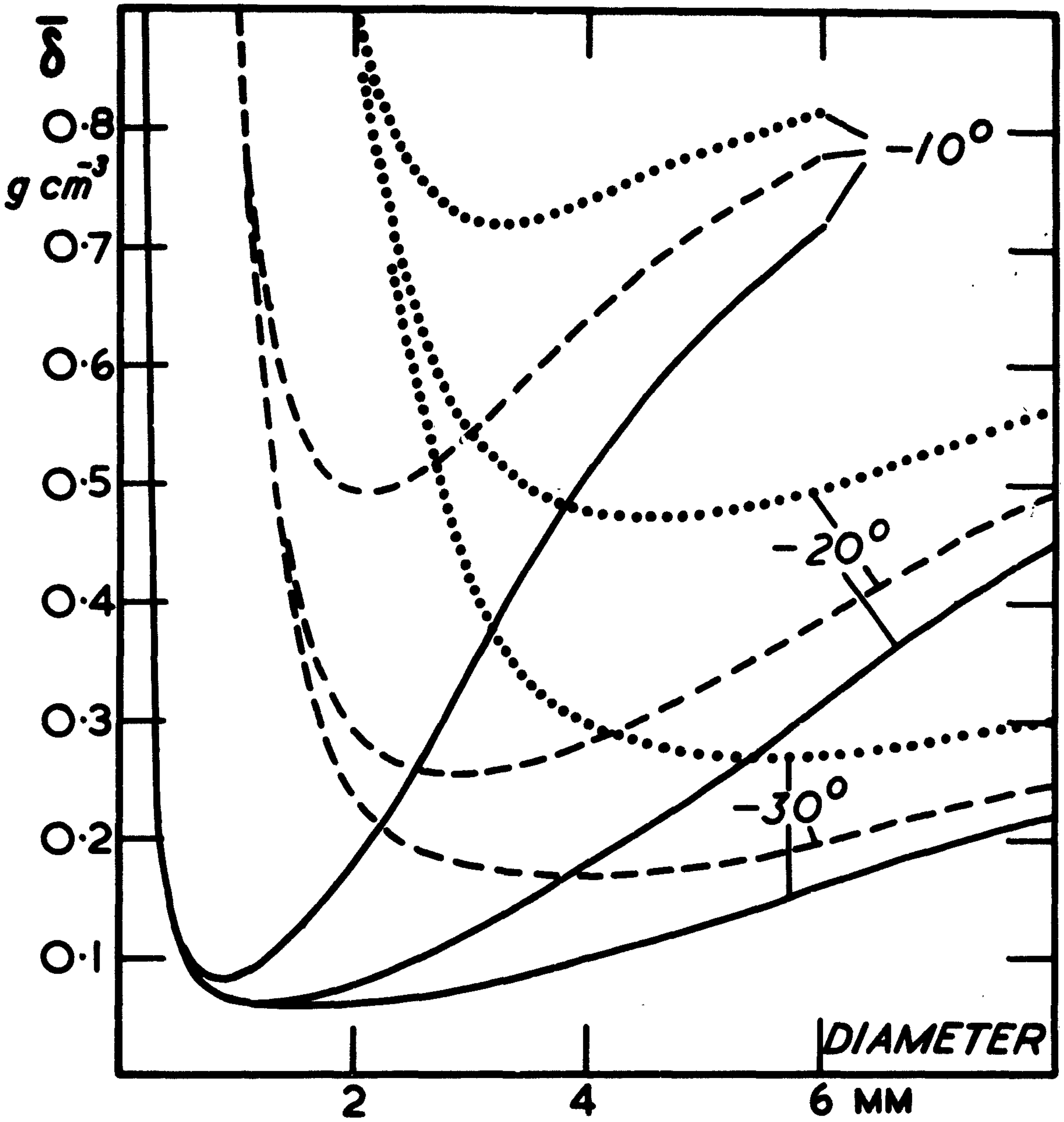

Fig. 2. Variation of mean density $\bar{\delta}$ of a hailstone (initial density 0.9 g cm^{-3} and initial diameter 200 microns, 1 mm, or 2 mm) growing at a constant temperature of -10°, -20° or -30°C in the cold-base cloud specified in the text.

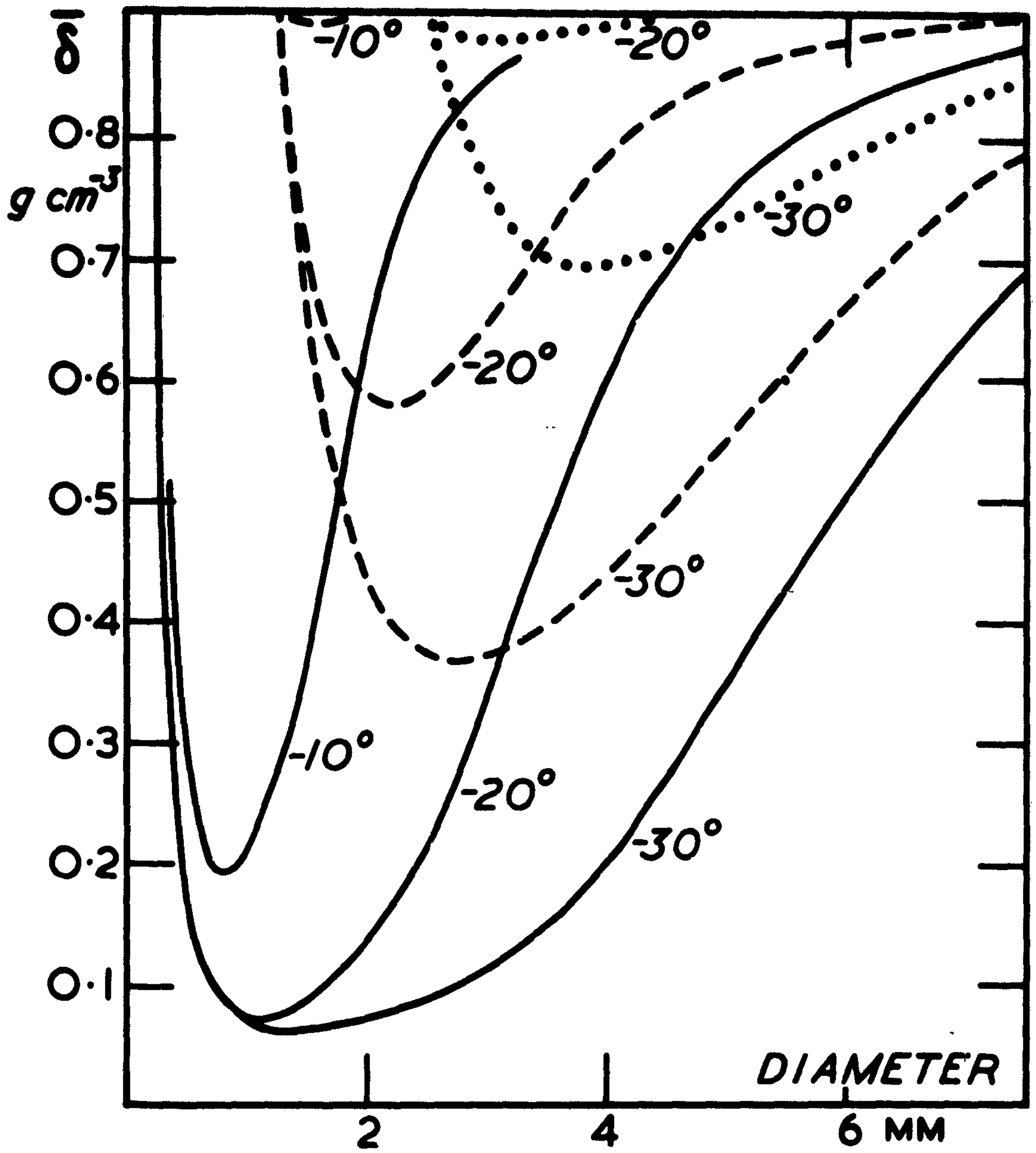

Fig. 3. Variation of mean density $\bar{\delta}$ of a hailstone (initial density 0.9 g cm^{-3} and initial diameter 200 microns, 1 mm, or 2 mm) growing at a constant temperature of -10°, -20° or $-30^{\circ}C$ in the warm-base cloud specified in the text.

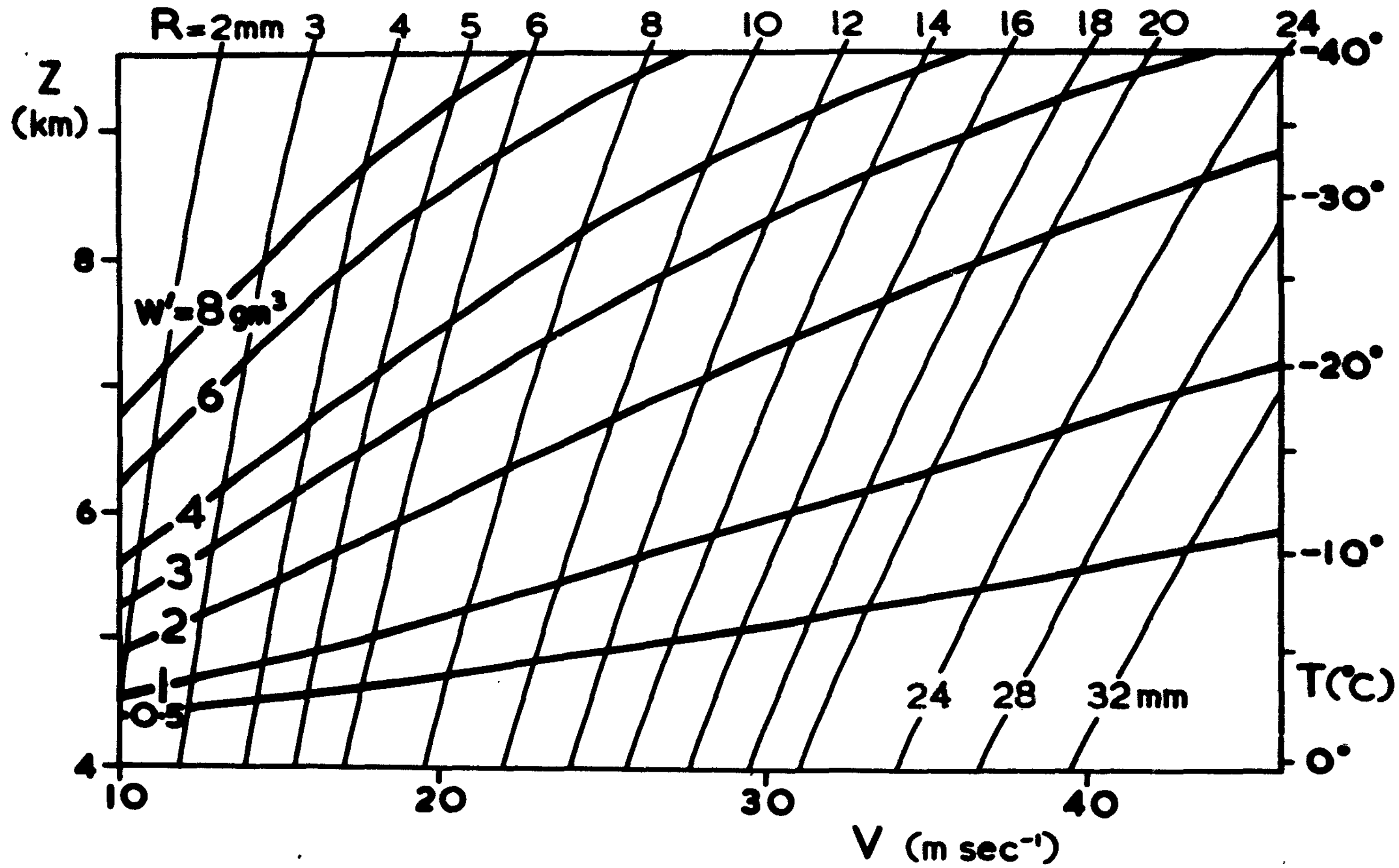

Fig. 4. Values of V and R, hailstone fall-speed and radius, at which the surface temperature is just 0°C, as a function of height z, at several values of the effective cloud-water concentration W' (conditions appropriate to a warm-base cloud in which the wet-bulb potential temperature is constant and equal to 19°C).

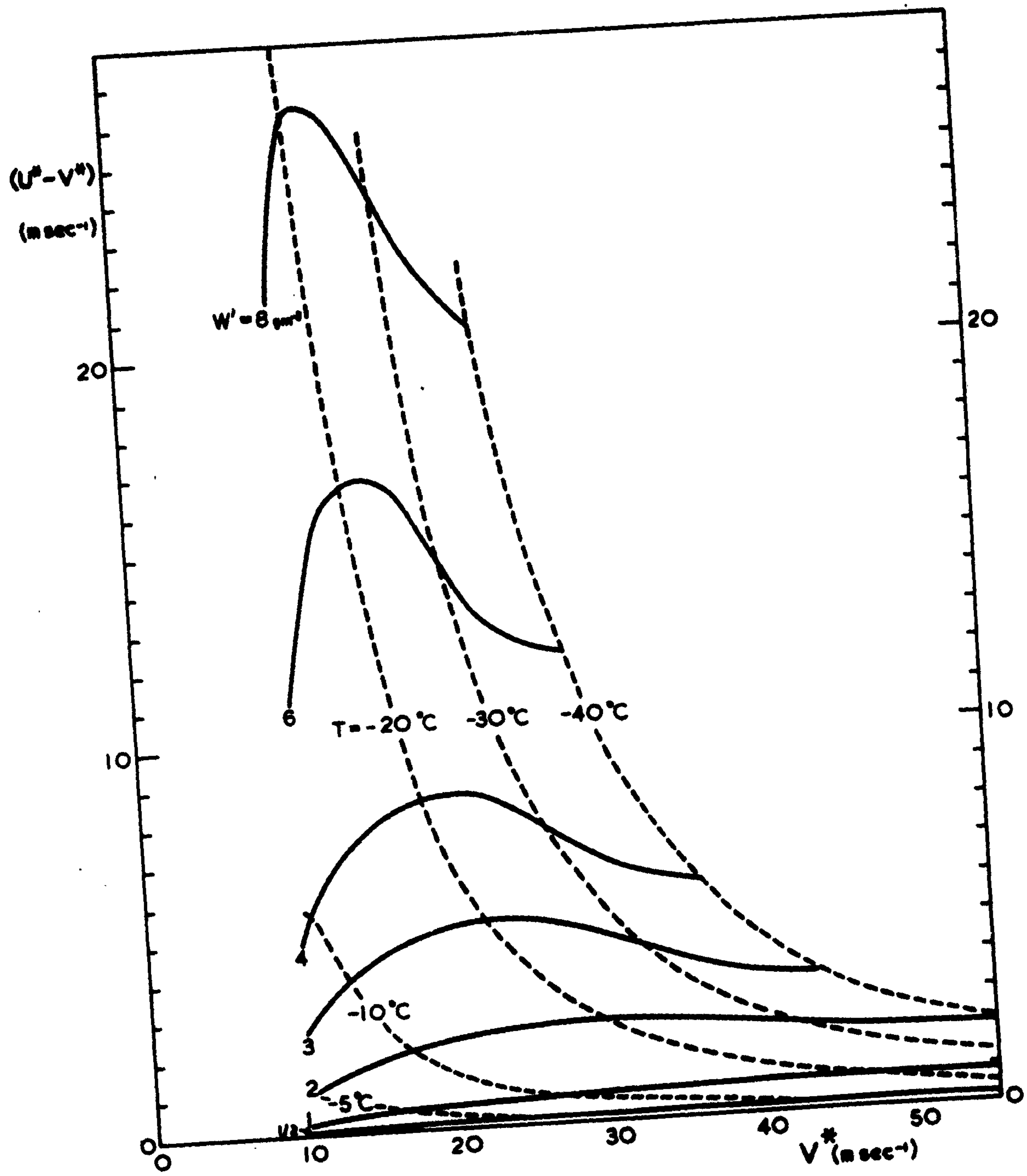

Fig. 5. $(U*-V*)$, i.e. the difference between the updraught speed and the fall-speed $V*$ of the hailstone whose surface temperature remains just 0°C during its ascent, as a function of $V*$ and the effective cloud water concentration W' (cloud conditions otherwise as noted below fig.4). Owing to the increasing drag coefficient at low Reynolds numbers all curves are terminated at $V* = 10$ m sec^{-1}.

Fig. 6

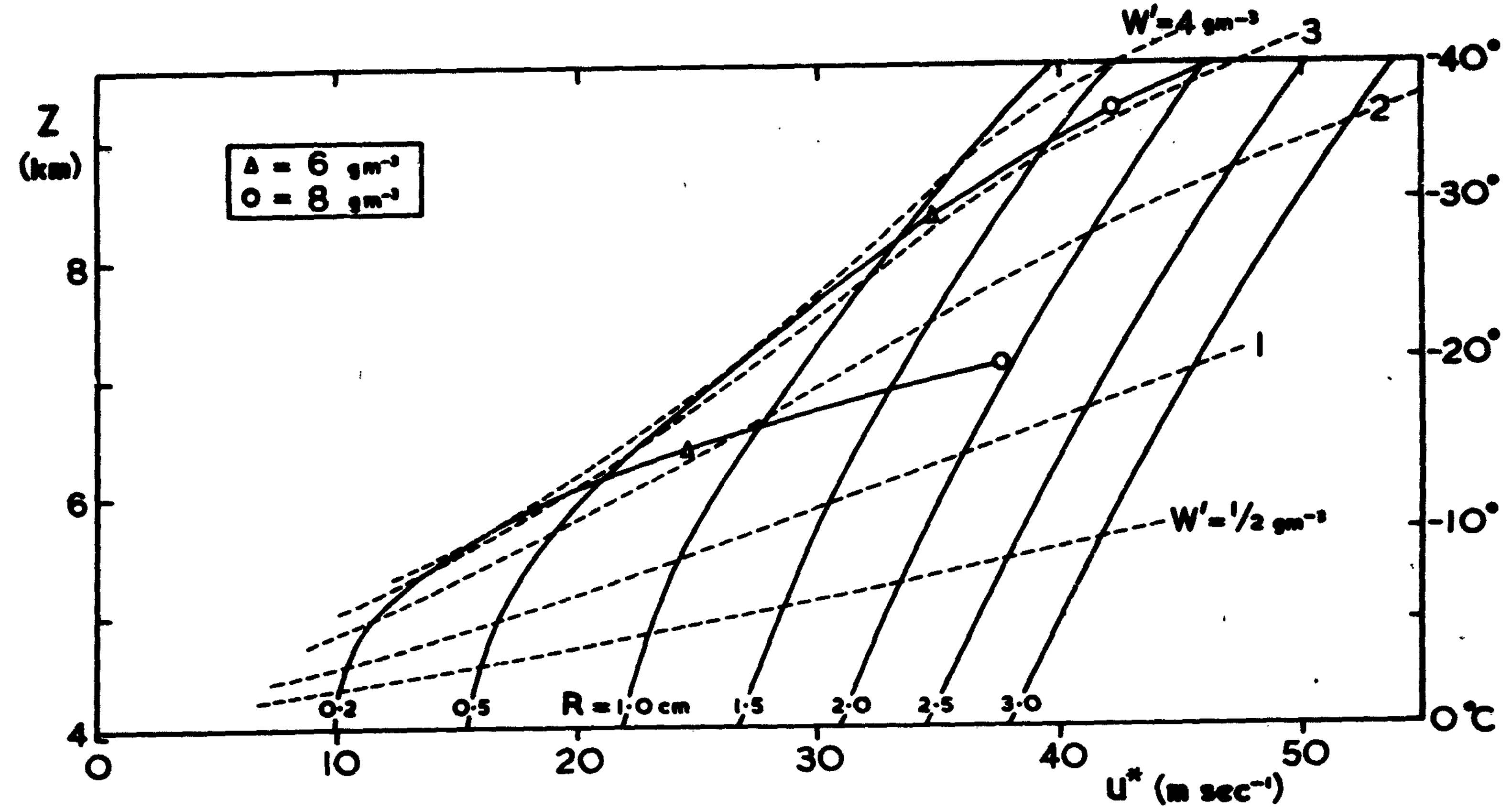

Fig. 6. The variation with height of the speed of the updraught U* in which the surface temperature of a growing hailstone may remain just 0°C, as a function of the cloud-water concentration W' (cloud conditions otherwise as noted below fig.4).