An important question about riming is: How large should a crystal be for riming to begin? Table 10.4 shows some field observations of the cutoff size for ice crystals of various types to commence riming.

Fig. 10.16 shows a plot of the "maximum" collision efficiencies of each crystal type as a function of their size. The size where \( E_{\text{coll}} \) drops to zero represents the cutoff size predicted by the numerical results. The agreement between the theory and

\[
E_{\text{coll}} = \frac{4 \cdot c^2}{R^2 + r^2}
\]

\( R \) and \( r \) are the radii of the ice crystal and the drop, respectively. The last data points (at large drop size end) for \( N_{\text{Re}} = 20 - 120 \) are extrapolated.
$E_{\text{coll}}$ of broad-branch crystals with droplets (10.15)

Fig. 10.15 Collision efficiency of crystals and supercooled drops. The last data points (at large drop size end) for $N_{\text{Re}} = 20$–120 are extrapolated. From Wang and Ji (2000). Reproduced by permission of the American Meteorological Society.

Fig. 10.16 Cutoff riming ice crystal sizes as extrapolated by the results shown in Figs. 10.13–10.15. For broad-branch crystals, the data point for crystal radius $2.5\text{ mm}$ was ignored when obtaining the best fit. From Wang and Ji (2000). Reproduced by permission of the American Meteorological Society.

Collision efficiency of crystals and supercooled drops

$E_{\text{coll}} = \frac{Re \cdot r}{J \cdot U_{cc}}$

neglected wake capture

Here $E_{\text{coll}}$ should leave the drop at the collector.
Cut-off rimming ice crystal sizes (Wang 10.16)
Stochastic collection equation (11.8)

\[
\frac{dn}{dr} = \frac{C(t)}{r^2} \left( \frac{dr}{dt} \right)
\]

where \( C(t) \) is the collection kernel given by Hocking and Jonas (1970) for drop radius \( a \leq 40 \mu m \) and by Shafrir and Neiburger (1963) for \( a > 40 \mu m \).

Unlike cloud droplet sizes in Chin and Neiburger (1972) that reach drizzle drops after ~30 min, Berry and Reinhardt (1974) yield millimeter-sized raindrops after 30 min. These figures again illustrate the sensitivity of rain formation to the initial drop size distribution in both the mean drop size and the spectrum. Comparing Fig. 11.8(a) and (c), where the mean drop radius is 10 and 12 µm, respectively, we can see that, by changing the mean radius a little, the latter evolves into mostly large cloud drop size (~30 µm) whereas the former only evolves into mostly large cloud drop size (~30 µm). Comparing Fig. 11.8(b) and (d), we can see that, for both cases with the same mean drop radius (14 µm), the one with Fig. 11.8(a) and (e) where the relative dispersion is 0.25 is mostly droplets, whereas the former only evolves into mostly large cloud drop size (~30 µm). Comparing Fig. 11.8(b) and (e), we can see that, for both cases with the same mean drop radius (14 µm), the one with Fig. 11.8(b) and (d) where the relative dispersion is 0.25 is mostly droplets, whereas the former only evolves into mostly large cloud drop size (~30 µm).
Growth by condensation and coalescence (11.9)

When drops are growing due to collision and coalescence, diffusion growth does not stop but can go on at the same time as long as the conditions are right. Although the diffusion growth rate is generally smaller than the collection growth rate, it has an amplification effect on the collection growth due to the above-mentioned size sensitivity of the spectrum. This effect was studied by Kovetz and Olund (1969) for supersaturation and shown clearly by Ryan (1974) as illustrated in Fig. 11.9.

Fig. 11.9 (a) The change in an initial drop distribution of $200 \, \text{cm}^{-3}$ after 500 and 1000 s when the Klett and Davis (1973) kernels are used. The dashed line shows the change after 1000 s when the shear kernel is used. (b) The effect of including condensation controlled by the wet adiabatic lapse rate and an updraft of $1 \, \text{m s}^{-1}$ with the coalescence equation. Adapted from Ryan (1974).
Muddiest points

- Why 2 peaks from disk break-up?
- Are all warm cloud rain events linked to GCCN over land?
- What def. of E is needed to explain Fig. 10.13-10.15? & 10.2?
- E collection - ice + drop - meaningful?
faster Bergeron process
Take home messages

- Giant CCN are responsible for warm rain formation over land.
- Initial cloud drop distr. is important for rain formation.
- Colloidal stability of the cloud linked to the drop size spectrum:
  - the narrower the drop size spectrum
  - the smaller the drops
  - the smaller the updraft velocity
  - the larger the CCN conc.
  - the absence of giant CCN
- Need stochastic growth to explain rain formation in obs. times.