Precipitation processes involve a complex mechanism in the atmosphere that produces raindrop-sized hydrometeors, in the milli-metric range, from diffusional condensation of water vapor in clouds and later collision and coalescence among the droplets formed through the diffusional processes (Brenguier and Chaumat, 2001; Beard and Ochs, 1993). Both of these processes are affected by entrainment of dry environmental air and turbulent mixing within the cloud. These factors show a tendency to broaden the drop size spectra. The droplet size larger than 40µm is critical for the initiation of the warm rain process (Brenguier and Chaumat, 2001). Pre-existence of large condensation nuclei in the cloud has been taken as a plausible reason for the existence of such large hydrometeors that initiate rainfall.

The number concentration of the CCN in the cloud affects the precipitation process. Large number concentration leads to smaller mean drop size than for smaller number concentration for the same liquid water content in the cloud. So the initiation of precipitation depends on the CCN spectrum and the liquid water content.

It clearly indicates that the mechanism of initiation of rainfall involves a complex process in the atmosphere and so model results calculated by using detail microphysics of the clouds and the dynamical aspects underestimate the initiation of precipitation by collision and coalescence process. Among the various factors affecting the large discrepancies in the model estimates and the real cloud situations are the processes of entrainment and turbulent mixing, limitations of the measuring instruments etc. In the case of droplet size spectra, in situ measurements may not tap the ultra giant nuclei, which play crucial role in the initiation of precipitation process, due to their small concentration and shorter lifetime.

Cloud Evolution and Droplet spectra Broadening
The broadness of the spectrum depends on a host of cloud characteristics e.g. the super saturation within the cloud and updraft speed (Yum and Hudson, 2005) but the spectrum becomes narrower as growth by condensation continues. The condensational growth rate is inversely proportional to the drop size (Equation 1) so if the growth were solely due to

\[
\frac{dr}{dt} = \frac{1}{r} \left( \frac{S - 1}{A + B} \right)
\]
condensation, larger hydrometeors would increase at a smaller rate and the smaller ones at higher rate resulting in narrowing of the spectrum. However, in real clouds, the spectra are broader than that predicted by condensation.

Cloud droplet broadening is directly related to the warm rain initiation process. Unless sufficiently large spectrum of drop sizes is formed collision-coalescence process can not be effective. So in clouds broadening of the spectrum should occur during the condensation phase. The actual spectrum observed in the clouds is broader than that predicted by the condensational growth (Yum and Hudson, 2005). The condensation phase produces some large droplets that facilitate collision-coalescence (collection) and increases collection efficiency.

Brenguier and Chaumat (2001) quote 40µm as the critical radius for the initiation of the warm rain process but the efficiency becomes significant only when some hydrometeors attain sizes above 100µm. Beard and Ochs (1993) show that the collection efficiency depends on the relative sizes of the collector drop and the collected droplet. The highest efficiencies are observed for collector drops of diameter 100 to 200µm and collected drops of 10 to 15µm.

Cloud evolution depends on the droplet spectra broadening process for some drops to attain the critical size required for facilitating the collection process. Various models have been used on the cloud evolution based on the dynamical and microphysical properties of the clouds. Kessler (1967) used parameterization approach to the microphysical processes, in which a threshold of 1gm⁻³ cloud LWC is taken as the limiting value for the rain making process. The model uses Marshall-Palmer distribution for the precipitation droplets. It uses linear relationship to relate rate of conversion of cloud liquid water (m) to precipitation water (M) for the case where the cloud LWC is greater than the threshold value, a, given by

\[ \frac{dM}{dt} = -\frac{dm}{dt} = K_i(m - a). \]

Once the large precipitation drops form, they grow by the accretion of LWC. In the model, the accretion growth rate is related to liquid water content of the clouds and the collection efficiency between the larger precipitation water distribution and the cloud droplets.

This model includes the cloud liquid water content but does not include the size distribution of the cloud droplets to include the effect of droplet size distribution. Berry (1968) included the effect of droplet size distribution in the conversion relationship. In the relationship, the rate of change of precipitation water is proportional to the cube of LWC and initial droplet dispersion and inversely proportional to the number density. The conversion relationship is given as

\[ \frac{dM}{dt} = \frac{m^2}{60\left[2 + \left(\frac{0.0266}{D_0}\right)\right]} N_0 \frac{N_0}{m}, \]

where \(D_0\) is the initial droplet radius dispersion and \(N_0\) is the concentration.

Latter models incorporated the cloud dynamics together with the cloud microphysics to get more realistic models. Hall (1980) described a model incorporating the dynamical aspects of the model and the microphysical properties. The model includes the effects of mixing of heat and moisture, advection of momentum and the cloud microphysics.

**Collision-Coalescence Process**

Collision and coalescence between faster moving larger drops and slower moving smaller drops is affected by the relative sizes of the drops, which affects the aerodynamic property, and the
number concentration of the drops. Beard and Ochs (1993) give a quantitative analysis on the collision-coalescence (collection) efficiency based on theoretical hydrodynamical effects and laboratory experiment. Figure 1 shows the collection efficiency as a function of collector drop radius (R) and collected droplet radii (r).

![Figure 1: Collection efficiency as a function of collector drop radius (R) and collected droplet radius (r).](image)

The efficiency of the collision-coalescence process and the evolution of the spectrum depend on the initial spectrum. Berry and Reinhardt (1974) show relationship between initial droplet spectrum and mean mass with the time evolution of the spectrum. It shows that when either of these two variables, variance of the drop size spectrum and its mean mass, is large the evolving spectra will be bimodal with large mean mass of the second mode. Figure 2(a-d) shows the temporal evolution of droplet spectra with varying size and variance. In the figure, $r_f$ and $r_g$ refer to the mean radius from the number density function and mass density function respectively and g is the mass density function. When the initial mean radius is 10µm and variance 1, the bimodal nature is not obvious and the increase in mean radius is small whereas for 12 µm mean radius and variance 1, the bimodal nature is obvious and starts as early as 15 minutes after the initiation. For 14µm mean radius and variance 0.25, the evolution is slower.

![Figure 2: Time evolution for initial spectrum of initial mean radius $r_f$ and variance of mass var (x).](image)

(a) $r_f = 10 \mu m$, var (x) = 1
than that of the 12µm mean radius and variance 1 though the mean mass is large, due to the smaller variance. For a 14µm mean radius and variance 1, the evolution is faster due to its larger size.

The in situ measurements reveal much broader droplet spectra than that predicted by models so there is a large uncertainty to what processes or factors increase the spectral broadness in real clouds. Brenguier and Chaumat (2001) point out three possible reasons for this observed broadness. The three reasons they put forward are: (i) Ultra giant precipitation embryos (UG Nuclei) pre-exist in clouds facilitating the growth by collision and coalescence, (ii) the actual efficiency of the collision-coalescence process is greater than estimated and (iii) there are processes within the clouds other than condensation to account for the broadening of the spectrum.

Condensational growth alone can not produce a spectrum with medium sized droplet of diameter 10 µm and large droplets of 40 µm unless UG nuclei pre-exist in the cloud. Such particles have been found and documented in marine clouds so they might serve to explain the precipitation process. These UG nuclei are necessary to produce such large hydrometeors with

Source: Berry and Reinhardt, 1974
diameter of 40 µm. Cooper et al. (1997) show that seeding large CCN in the clouds increase the collision coalescence rate. Seeding a cloud with hygroscopic nuclei larger than the ones naturally present in the clouds increases the formation of larger rain-sized drops. Figure 3 shows the effect of cloud seeding with larger droplets in the evolution of the drop size distribution with time in 20, 600, 1200 and 1800 seconds. The time is for uniformly ascending parcel starting from the cloud base.

Figure 3: The mass distribution function 20, 600 (dotted), 1200 (dashed), 1800 seconds after passing through the cloud base. The thick line curves in b for the distribution including larger drops and thin lines excluding the larger drops.

Source: Cooper et al., 1997

Though droplet spectra is a major contributor for the precipitation process model calculated values and the in situ measurements show large discrepancies. The discrepancies arise due processes such as entrainment of dry environmental air and mixing within cloud and instrumental limitations. Brenguier and Chaumat (2001) show that for Fast-Forward Scattering Spectrometer Probe (FSSP) the instrumental uncertainty and averaging do not play important role in the observed discrepancies so they can be attributed to entrainment, turbulent mixing gravitational effects etc.

Turbulent Mixing and Entrainment
Turbulent mixing and entrainment in clouds are other possible causes for the discrepancy seen between the model output and the in situ measurements. Entrainment causes dilution of cloud and may cause evaporation of smaller drops with decrease in vapor pressure giving more opportunity for larger droplets to grow with lesser competition. Turbulent mixing causes redistribution of droplets giving rise to differing growth rates of similar sized drops. This redistribution affects the growth rate differently at the two phases of growth. Due to turbulence, there is microscale fluctuation in the super saturation field (Brenguier and Chaumat, 2001), which causes the presence of vorticity maxima and minima (Shaw et al., 1998). In turbulent flow field, the drop concentration is higher in regions of low vorticity. So, regions of high vorticity have smaller drop concentration and thus higher super saturation. This condition prevails in the presence of turbulent flow field and is independent of the mean vertical velocity.
Droplets growing in the high super saturation of the high vorticity region experience faster condensational growth rate than their similar sized particles in lower super saturation region. This leads to different growth rate among the same sized hydrometeors. This is one of the causes the broadening of the droplet size spectrum in clouds. When the collection phase is the dominant process, the effect is reverse, with larger drops growing faster at high droplet concentration areas due to higher collision probabilities.

Riemer and Wexler (2005) used box model and simulated the development of cloud droplet spectra using coagulation kernel. This coagulation kernel incorporates the effect of turbulence on both the relative velocity of the droplets and the local change in droplet concentration. It shows that as turbulence (expressed as eddy dissipation rate) increases the liquid water content is dominated by larger drops indicating production of larger hydrometeors. Figure 4 shows the temporal evolution of the mass size for the model used.

Figure 4: Temporal evolution of mass size distribution

Conclusion
Turbulence in the condensation phase is a major cause of the discrepancy observed between the classical condensation model and the real droplet spectra. It causes microscale variation in the supersaturation within the cloud, which affects the growth rate of the initially similar sized drops. Pre-existence of UG nuclei in the cloud also affects in broadening the spectra in real clouds. After some clouds reach the size necessary for collision and coalescence, they grow by collecting smaller droplets. Turbulence within the cloud causes variation in droplet concentration and the larger particles grow at a faster rate in the region with larger drop size concentrations.

References