Entrainment and droplet spectral characteristics in convective clouds during transition to monsoon

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1. Introduction

Cumulus clouds are widely prevalent over tropical region and contribute significantly to the global radiative forcing and hydrological cycle (Morrison and Grabowski, 2007). Studying their characteristics is important to understand the cloud development and warm rain process (Devenish et al., 2012). Entrainment of dry air in cumulus clouds has been a subject of numerous studies due to its importance in several dynamical and microphysical processes (Paluch and Baumgardner, 1989; Grabowski, 2007). Entrainment in cumulus clouds impacts microphysical parameters significantly and aerosol pollution can modify the entrainment response on cloud properties (Jiang et al., 2006). One of the fundamental problems in cloud physics is to understand the rapid onset of warm rain process (Tolle and Krueger, 2014), which can be either linked to droplet size distribution (DSD) broadening by entrainment-mixing mechanisms (Lasher-Trapp et al., 2005) or to the microphysics of less diluted cloud core (Blyth et al., 2005). Broadening of DSD produced by entrainment-mixing is responsible for accelerating coalescence growth (Berry and Reinhardt, 1974) and is also important for radiative properties of the clouds (Lasher-Trapp et al., 2005). Representation of entrainment and impact on microphysics accurately in climate models is needed (Tolle and Krueger, 2014) and in situ observations have great value in this respect, especially over South Asia where these processes in monsoon clouds are less understood.

The width of cloud core decreases in polluted environment due to enhanced evaporation rate (Seigel, 2014). Possibility of evaporation-entrainment feedback in polluted cumulus clouds is also suggested (Jiang et al., 2006; Small et al., 2009) and lateral entrainment may impact width of cloud core where adiabatic cloud properties are preserved. It could be hypothesized that lateral entrainment dilutes the cloud edges but an inner core remained with maximum liquid water content (LWC) and droplet number concentration, which is quite different for a pre-monsoon and a monsoon cloud. So, the cloud volume can be separated in two parts: an inner core (less diluted) and a shell (highly diluted) surrounding the core. The strength of entrainment dictates the possible width of the inner core.

Entrainment broadens the DSD and produces dispersion in droplet size spectra (Lu et al., 2008). Spectral width ($\sigma$) is the standard deviation of DSD and relative dispersion ($\epsilon$) is the ratio of spectral width to mean radius ($<r>$) (Lu et al., 2008). Dispersion effect can offset the Twomey cooling (Twomey, 1974) in polluted clouds (Liu and Daum, 2002) and sometimes up to 39% (Pandithurai et al., 2012) using in situ observations. Relative dispersion (varies within a narrow range of 0.25–0.35 for warm convective clouds observed over Istanbul region) is not correlated with the droplet number concentration ($N_d$) or LWC of the clouds but the variance of relative dispersion changes with $N_d$ and LWC (Tas et al., 2015). Higher variance was associated with low $N_d$ and LWC typically at cloud edges, due to lateral entrainment. Most of the studies discussed lateral entrainment in shallow cumulus or stratocumulus and very less attention is given to the deep cumulus with a few (3–4) kilometer depth. Shallow cumulus is dominated by cloud top entrainment (Paluch, 1979) whereas lateral entrainment is more significant in deep cumulus (Boing et al., 2014). Deep cumulus that forms a significant component of the monsoon cloud systems might exhibit dilution much inside of the clouds due to larger vertical extent unlike the shallow cumulus where dilution is limited to outer cloud shell driven by buoyancy gradient (Heus and Jonker, 2008; Small et al., 2009). The dynamics of deep cumulus is also greatly
influenced by environmental thermodynamics (Prabha et al., 2011). It was also noted that rain drop formation process in these clouds is more favorable in the cloud core region (Khain et al., 2013). This study is aimed to understand the cloud edge entrainment and core dispersion characteristics while transition to monsoon happened over the Indian peninsula. The effect of entrainment on DSD and spectral dispersion in deep cumulus clouds is discussed as a function of distance from the cloud core.

2. Experiment and methodology

The study used the in situ cloud observations of growing cumulus taken during the Cloud Aerosol Interaction and Precipitation Enhancement Experiment phase-I (CAIPEEX-I), conducted over peninsular India during June 2009. Each flight corresponds to about 2 h of observation at 1 Hz (100 m) but only cloud penetration data are mainly used for detailed microphysical analysis. Number of clouds and number of samples used in the study are indicated in Table 1. A detailed description of the instruments and overview of the experiment is provided by Kulkarni et al. (2012). The case studies (15, 16, 21 and 22 June) considered here are deep cumulus-congestus clouds observed over Hyderabad (17.45°N, 78.46°E) during transition to summer monsoon period. The same observations are used as representative of pre-monsoon (15, 16 June) and monsoon (22 June) clouds (Prabha et al., 2011, 2012; Khain et al., 2013; Bera et al., 2016). Cloud droplet probe (CDP) and a hot-wire sensor are used to measure droplet size and LWC, respectively. Passive cavity aerosol spectrometer probe (PCASP) measured aerosol number concentration (range 0.1–30 μm). Temperature and humidity are measured by AIMMS-20 probe. Several horizontal penetrations lasting few seconds are conducted at different levels at and above cloud base. The observations presented here are from growing cumulus which is conditionally probed to fulfill the objective of the experiment. The growth stage of cloud is also validated by observing incloud vertical velocity from cloud base to 1 km above and found more than 80% of the cloud penetration data having updraft, as described by Gerber et al. (2008) to select growing cumulus. Aircraft observations taken at a frequency of 1 Hz corresponds to about 100 m spatial resolution. The cloud samples were selected from the warm region of cloud, without any precipitation size drops in DSD as also verified with the help of a cloud imaging probe (as described by Prabha et al., 2011). A threshold droplet number concentration (N_d) of 10 cm⁻³ as followed by Rangno and Hobbs (2005) is used to identify the incloud samples. Adiabatic liquid water is calculated by using the linear relationship LWC_ad = C_w h, where C_w is the condensation rate and h is the height above cloud base (Brenguier, 1991). Adiabatic fraction (AF) is the ratio of LWC and LWC_ad. Cloud core width is determined by the cloudy region with highest LWC and AF (>0.4). Distance from highest LWC point to cloud edge (N_d < 10 cm⁻³) is used to normalize the distance (between 0 and 1).

Mixing fraction of cloudy mass (χ), i.e the ratio of adiabatic cloudy mass at cloud base and total mass after entrainment (adiabatic cloudy air + dry entrained air) at height level z above cloud base, is used to estimate fractional entrainment rate (λ) by following the approach of Lu et al. (2012a) and detailed description of this methodology is provided in Appendix S1. Entrainment rate (λ) is estimated as

\[ \lambda = \frac{\ln \chi}{h}, \]  

where χ is the mixing fraction of the cloudy air at height level h above the cloud base. We used integrated mixing fraction (χ) between cloud base and the observation level and averaged fractional entrainment rate (cf. Appendix S1 for details). Mixing fraction approach for estimating entrainment rate has advantage as measurement of incloud temperature and water vapor is not required that may have errors due to wetting of sensors. This method can be applied in remote-sensing technique to estimate entrainment rate. This approach also connects the estimation of entrainment rate directly to the microphysical effect of entrainment (Lu et al., 2014), and could be intercompared with similar estimates from remote sensing.

3. Results and discussion

The study discusses the effect of entrainment on microphysics and core width of cumulus clouds developing

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Table 1. Summary of the flights (15, 16, 21 and 22 June) which are been used in the article. Number of clouds and number of samples correspond to warm cloud region only and the same have been presented in the article. Sub-cloud aerosol number concentration (N_a) is measured by PCASP. CDP observed mean (warm cloud) droplet number concentration (N_d) and droplet effective diameter (D_e) are presented here. Environmental RH corresponds to out cloud samples. Sub-cloud updraft is observed at 100 m below cloud base by AIMMS probe.

| Flight date | No. of clouds | No. of samples | Cloud base (m) | N_d (cm⁻³) | N_a (cm⁻³) | D_e (μm) | RH (%) in boundary layer | RH (%) in cloudy layer | Sub-cloud updraft (m s⁻¹) |
|-------------|---------------|----------------|---------------|-------------|------------|---------|------------------------|------------------------|------------------------|
| 15 June     | 14            | 186            | 2813          | 9.36 ± 1.17 | 323.7 ± 11.82 | 12.14 ± 1.64 | 59.8 ± 12.6 | 74.0 ± 4.1 | 1.77 ± 1.12 |
| 16 June     | 18            | 192            | 2709          | 117.8 ± 22.68 | 50.1 ± 24.26 | 12.26 ± 1.78 | 57.2 ± 15.4 | 73.4 ± 3.3 | 1.68 ± 1.32 |
| 21 June     | 14            | 156            | 2452          | 96.7 ± 19.45 | 417.3 ± 16.95 | 13.06 ± 1.67 | 63.5 ± 12.3 | 78.4 ± 7.8 | 1.57 ± 1.21 |
| 22 June     | 15            | 180            | 2062          | 33.0 ± 6.93 | 186.5 ± 35.2 | 16.98 ± 2.83 | 72.1 ± 11.9 | 77.8 ± 6.4 | 1.82 ± 1.35 |

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under varying aerosol and thermodynamic conditions (transition to monsoon). The large-scale meteorological conditions are depicted in Figure S1, Supporting Information. The wind vectors at 850-mb pressure level show that south-westerly wind dominated over Hyderabad on 22 June (as an indication of monsoon onset). Vertical variation of potential temperature ($\theta$) and water vapor mixing ratio ($q_v$) from radiosonde measurements are shown in Figure S2. Boundary layer temperature decreases and moisture content increases after the onset of monsoon. It may be noted that depth of the atmospheric boundary layer (ABL) and cloud base height (Table 1) decreases as monsoon sets, compared to pre-monsoon days due to high moisture transport and low incoming solar radiation reducing surface heating. Thermodynamic and microphysics of pre-monsoon and monsoon clouds are discussed by Prabha et al. (2011) and Bera et al. (2016). The summary of the flights which is presented in Table 1 shows highest sub-cloud aerosol number concentration ($N_e$) on 16 June (1178 cm$^{-3}$) and after onset $N_e$ reduced to 330 cm$^{-3}$ on 22 June. Other two cases (15 and 21 June) are moderately polluted. RH in the boundary layer increases progressively with the monsoon onset although mid-layer RH remains closely same. Monsoon cloud (22 June) has the largest effective diameter and least droplet number concentration (Table 1). Sub-cloud updraft is similar (1.5–1.8 ± 1.2 ms$^{-1}$) in all clouds. The information of cloud samples and number of clouds during each flight used in the study is presented in Table 1.

The DSD as a function of droplet diameter ($D$) during the four flights is shown in Figure 1. DSD is shown for entire flight (cloud base to cloud top) which is not used for the rest of the analysis as we are focusing on warm and non-precipitating part of the clouds. The altitude of flight observation, corresponding effective diameter ($D_e$), distance from cloud core and spectral width of DSD are depicted on the top of each DSD at 1 Hz. Relatively small droplets ($D < 30 \mu m$) are observed in pre-monsoon clouds (15, 16 June) with narrow spectral width compared to the clouds on 21 and 22 June, which produced larger droplets ($D > 30 \mu m$) and broadened DSDs. Precipitation size droplets ($D > 24 \mu m$) are formed above 4 km altitude on 22 June (which is not considered for later part) and characterized by broader DSDs in contrast to other three clouds. The threshold for rain drops to form is $D_e > 24 \mu m$ is reported by Pinksky and Khain (2002) and Rosenfeld et al. (2002). The dash line (black) on the top panel of Figure 1(a)–(d) indicates the height level, below which incloud data are used for the main analysis of the study. The figure provides valuable information of spectral width as a function of distance from cloud core at different altitudes. This shows that spectral width and the distance from cloud core are in negative correlation for pre-monsoon clouds (higher spectral width at cloud core) but positively correlated for monsoon cloud (indicated vertical black line in the sub plot). Information of droplet number concentration ($N_d$) averaged within the warm region of cloud is provided in Table 1. $N_d$ is observed to be higher in all clouds except for 22 June (monsoon cloud). Entrainment of dry air and subsequent mixing dilutes the cloudy mass. Due to dilution both LWC and $N_d$ reduces. Figure 2(a) shows observed $N_d$ in highly diluted (AF < 0.4) and slightly diluted (AF > 0.4) cloud samples at different altitude levels. We see that $N_d$ significantly reduces in the highly diluted region compared to slightly diluted region in case of pre-monsoon clouds but the changes are very less in monsoon cloud. Another aspect is that the variance of $N_d$ (represented by the error bars) at different altitude levels is much higher in the highly diluted part of the pre-monsoon clouds. These variances are associated with the evaporation of droplets in the highly diluted cloud samples. Most of these cases show a continued increase in $N_d$ above the cloud base (mainly in the slightly diluted part of the warm cloud, cf. Figure 2(a)). This is attributed to the incloud activation as already discussed in the previous study (Prabha et al., 2011). In spite of significant reduction in droplet number concentration, effective radius of droplets does not show any significant changes between highly diluted and slightly diluted cloud volumes in both pre-monsoon or monsoon clouds (figure not presented).

3.1. Impact of lateral entrainment on cloud core width

For studying entrainment effect, we have selected only long cloud passes with a minimum pass time of 6 s (600 m length) as followed by Small et al. (2009). Probability distribution of AF (Figure 2(b)) shows that polluted clouds are more adiabatic (AF > 0.7 exists in pre-monsoon clouds only) in cloud core region but the probability of higher AF (>0.4) decreases sharply which suggests a narrow convective core (samples number is less). In case of the monsoon cloud, the probability of higher AF (>0.4) remained almost constant at higher value which is in contrast to the pre-monsoon clouds where rapid decrease is seen. This result suggests that lateral entrainment impacts the core width of pre-monsoon and monsoon clouds differently. A new analysis is presented to investigate the entrainment effect on cloud core width based on maximum LWC. AF is varied as a function of distance (normalized) from highest LWC region (Figure 3). Convective core is retained with maximum LWC (or AF) and as we move from convective core to cloud edges, LWC (or AF) decreases gradually. The width of cloud core is the distance over which AF remained high (>0.4). Cloud penetrations at different altitude levels (color code represents height above cloud base) are considered with a threshold penetration time of 10 s which is about 1 km penetration length so that convective core exists in between the cloud edges. Number of clouds used in the analysis (Figure 3(a)–(d)) indicated by marker legend correspond to each cloud pass. One of the important results is a sharp reduction of AF within first 30–40% distance is observed in case of polluted pre-monsoon
clouds but monsoon cloud shows a slower decrease of AF and indicates a wider core possibly due to weaker entrainment. The linear fit (black line) also indicate similar results where AF decreases more rapidly (higher negative slope) with distance from core in pre-monsoon clouds but in case of monsoon cloud, AF decreases slowly (lower negative slope) with distance from core. As the distance is normalized by core to edge distance, the actual width of cloud core may vary for different cloud penetration. For a 2 km cloud penetration length the width of cloud core will be around 600–800 m in pre-monsoon cases. It may also be noted that the AF in the core region is higher in the pre-monsoon clouds compared to the monsoon cloud. The monsoon cloud is also less adiabatic at lower elevation and more adiabatic in the core region at 2 km height above cloud base (this is observed in selected cloud penetration samples but is not an overall feature), however, in a pre-monsoon cloud, throughout the warm region, the high adiabatic region (though narrow) may be noted.

Figure 3(e)–(h) shows the PDF for AF > 0.4 and AF < 0.4 as a function of the distance from highest LWC point. The probability of higher AF (>0.4) is reduced drastically as the distance increases in case of polluted pre-monsoon clouds. This essentially implies that less-diluted region (or cloud core) exists in a very narrow region close to the highest LWC point. So, these cumuli are mostly diluted even several hundred meters inside of the cloud due to lateral entrainment. But monsoon cloud (Figure 3(h)) has relatively wider core so that higher AF (>0.4) can exists even far away from the highest LWC point.

3.2. Droplet spectral characteristics

Now, we will discuss the effect of entrainment on droplet spectral width (σ) and relative dispersion (ε), which are important parameters used in cloud models. Figure 4(a)–(d) shows joint probability distribution of spectral width and distance from highest LWC point. Spectral width in monsoon cloud is observed higher than polluted pre-monsoon clouds which is in agreement with previous studies (Prabha et al., 2011, 2012; Bera et al., 2016). Higher values of spectral width are also observed in a region of highest LWC (also reported by Prabha et al., 2012) and as we
move towards cloud edges spectral width decreases in all clouds except the monsoon cloud (22 June). The changes of spectral width at cloud edges (highly diluted region) of pre-monsoon clouds are mainly associated with lateral entrainment but collision-coalescence may contribute to DSD change in monsoon cloud where larger droplets are present. The result suggests opposite response (narrowing of DSD) of deep cumulus clouds in dry pre-monsoon condition compared to the shallow cumulus where broadened DSDs are observed due to entrainment mixing (Tölle and Krueger, 2014 and reference therein). The monsoon cloud, however, shows contrasting behavior where higher spectral width is seen for samples far away from highest LWC point. The appearance of higher $\sigma$ in the highly diluted cloud edge region of monsoon cloud could be caused by
collision-coalescence of the larger droplets (Devenish et al., 2012) which are not present in pre-monsoon clouds (Prabha et al., 2011). As the environment is moist and aerosols near clouds are pre-moistened as illustrated by (Konwar et al., 2015), there is partial evaporation of droplets, which broaden the spectra in downdrafts and may activate in cloud updrafts. The presence of collision-coalescence in monsoon deep convective cloud is reported by Prabha et al. (2011) and Khain et al. (2013). It is also evident from Figure 4 that probability is higher only close to highest LWC region in pre-monsoon clouds but there exists higher probability even close to cloud edge region in monsoon cloud. Relative dispersion (Figure 4(e)–(h)) in polluted pre-monsoon clouds is higher than observed in monsoon cloud which is in agreement with the previous study by Pandithurai et al. (2012). Inside the cloud core relative dispersion has a range of 0.3–0.4 in pre-monsoon clouds and 0.2–0.3 in monsoon clouds. In all pre-monsoon cases, relative dispersion remained almost constant with distance from highest LWC point which is in agreement with Tas et al. (2015), who reported that relative dispersion does not vary with LWC or $N_d$. It should be pointed out that the higher variances noted are due to the cloud edge entrainment. However, monsoon cloud has distinct feature

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3.3. Entrainment rate

The above results suggest that entrainment impacts the cloud core width and microphysical parameters distinctly in pre-monsoon and monsoon clouds. Changes in entrainment rate are used to explain the observed cloud features. Vertical distribution of fractional entrainment rate ($\lambda$) and mixing fraction ($\chi$) is investigated in Figure 5 by adapting the methodology as suggested by Lu et al. (2012a). Cumulus clouds entrain dry air during its development stage and as a result mixing fraction of cloudy mass reduces as it deepens. So, for higher entrainment rate, mixing fraction becomes smaller. Mixing fraction at any specific level above cloud base indicates the degree of mixing of cloudy volume with the environmental air in comparison with the cloud base. It is almost same at cloud base height (ideally equal to 1.0) but as depth increases clouds are getting mixed with their close environment and fraction of cloudy mass decreases. At any height level, pre-monsoon polluted clouds have lower fraction of cloudy mass. Thus the pre-monsoon clouds are relatively more mixed ($\chi$ is smaller) with the environment than the monsoon cloud. Vertical distribution of fractional entrainment rate ($\lambda$) also indicates similar results (Figure 5). Higher entrainment rate is observed in polluted pre-monsoon clouds and lowest entrainment rate is seen in less polluted monsoon cloud (22 June) at any height levels except the cloud base. The results discussed above support the argument that polluted pre-monsoon clouds exhibit stronger entrainment which impacts cloud microphysical parameters significantly. The entrainment rate observed here is comparable with the previous studies (Gerber et al., 2008; Lu et al., 2012a).

4. Conclusion

The entrainment and spectral characteristics of clouds during the transition to monsoon period over southern peninsular region were investigated using in situ airborne observations. The entrainment of unsaturated environmental air decreases $N_d$ significantly in the highly diluted regions compared to less diluted volume in pre-monsoon cases. Lateral entrainment produces higher variance of $N_d$ due to droplet evaporation in most diluted part. Analysis based on the highest LWC point indicates that less-diluted region of the pre-monsoon clouds is much narrow compared to the monsoon cloud where a wider cloud core is found. Enhancement of entrainment rate is observed in polluted pre-monsoon clouds where high aerosol concentration in combination with environmental conditions favor cloud development. Spectral width of DSD is found to decrease in the highly diluted region of pre-monsoon clouds associated with droplet evaporation which is in contrast to the shallow clouds where broadening of DSD due to entrainment-mixing is reported in many previous studies. But after transition to monsoon, it is observed that spectral width increases in the highly diluted part which can be due to collision-coalescence process active in monsoon cloud as well as the partial evaporation and activation (as shown by Prabha et al., 2011). Relative dispersion ($\epsilon$) remained nearly constant with varying distance from cloud core in case of polluted pre-monsoon clouds but opposite effect is observed in less polluted monsoon cloud where relative dispersion increases significantly at cloud edges where higher spectral width is observed.

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Supporting information

The following supporting information is available:

Appendix S1. Calculation of entrainment rate.

Figure S1. Contour plot of sea level pressure (SLP) and wind vector at 850 mb pressure level. The location of experiment (Hyderabad) is marked by black square.

Figure S2. Vertical profile of environmental potential temperature ($\theta$) and water vapor mixing ratio ($q_v$) from radiosonde observation.

Figure S3. Variation of (a) averaged spectral width, (b) averaged relative dispersion, (c) standard deviation of spectral width and (d) standard deviation of relative dispersion as a function of distance from highest LWC point. Four flights are represented by different colors and markers as indicated in (a).

References

Bera S, Prabha TV, Grabowski WW. 2016. Observations of dynamics-microphysics interactions in convective clouds over the Indian subcontinent (under review).

Berry EX, Reinhardt RL. 1974. An analysis of cloud drop growth by collection. Part II: single initial distributions. Journal of Atmospheric Science 31: 1825–1831.

Böing SJ, Jonker HJ, Nawara WA, Siebesma AP. 2014. On the deceiving aspects of mixing diagrams of deep cumulus convection. Journal of Atmospheric Science 71: 56–68.

Blyth AM, Lasher-Trapp SG, Cooper WA, 2005. A study of thermals in cumulus clouds. Quarterly Journal of the Royal Meteorological Society 131: 1171–1190.
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Lu C, Liu Y, Niu S, Endo S. 2014. Scale dependence of droplet size distributions from entrainment and mixing in a cumulus cloud. *Quarterly Journal of the Royal Meteorological Society* 131: 195–220.

Liu Y, Daum PH. 2002. Indirect warming effect from dispersion forcing. *Nature* 419: 580–581.

Lu M-L, Feingold G, Jonsson HH, Chuang PY, Gates H, Flagan RC, Seinfeld JH. 2008. Aerosol-cloud relationships in continental shallow clouds. *Journal of Geophysical Research* 113: D15201.

Lu C, Liu Y, Yum SS, Niu S, Endo S. 2012a. A new approach for estimating entrainment rate in cumulus clouds. *Geophysical Research Letters* 39: L04802.

Lu C, Liu Y, Niu S, Vogelmann AM. 2012b. Observed impacts of vertical velocity on cloud microphysics and implications for aerosol indirect effects. *Geophysical Research Letters* 39: L21808.

Lu C, Liu Y, Niu S, Endo S. 2014. Scale dependence of entrainment-mixing mechanisms in cumulus clouds. *Journal of Geophysical Research: Atmospheres* 119: 13,877–13,890.

Morrison H, Grabowski WW. 2007. Comparison of bulk and bin warm-rain microphysics models using a kinematic framework. *Journal of Atmospheric Science* 64: 2839–2861.

Paluch JR. 1979. The entrainment mechanism in Colorado cumuli. *Journal of Atmospheric Science* 36: 2467–2478.

Paluch JR, Baumgardner DG. 1989. Entrainment and fine scale mixing in a continental convective cloud. *Journal of Atmospheric Science* 46: 261–278.

Pawlowska H, Grabowski WW, Brenguier J-L. 2006. Observations of the width of droplet spectra in stratocumulus. *Geophysical Research Letters* 33: L19810.

Pandithurai G, Dipu S, Prabha TV, Maheskumar RS, Kulkarni JR, Goswami BN. 2012. Aerosol effect on droplet spectral dispersion in warm continental cumuli. *Journal of Geophysical Research* 117: D16202.

Pinkny M, Khain A. 2002. Effects of in-cloud nucleation and turbulence on droplet spectrum formation in cumulus clouds. *Quarterly Journal of the Royal Meteorological Society* 128(580): 501–533.

Prabha TV, Khain A, Maheskumar RS, Pandithurai G, Kulkarni JR, Konwar M, Goswami BN. 2011. Microphysics of pre-monsoon and monsoon clouds. *Journal of Atmospheric Science* 68: 1882–1901.

Prabha TV, Patade S, Pandithurai G, Khain A, Axisa D, Pradeep Kumar P, Maheshkumar RS, Kulkarni JR, Goswami BN. 2012. Spectral width of pre-monsoon and monsoon clouds over Indo-Gangetic valley. *Journal of Geophysical Research* 117: D20205.

Rangno AL, Hobbs PV. 2005. Microstructures and precipitation development in cumulus and small cumulonimbus clouds over the warm pool of the tropical Pacific Ocean. *Quarterly Journal of the Royal Meteorological Society* 131: 639–673.

Rosenfeld D, Lahav R, Khain A, Pinkny M. 2002. The role of sea spray in cleansing air pollution over ocean via cloud processes. *Science* 297(5587): 1667.

Seigel RB. 2014. Shallow cumulus mixing and subcloud-layer responses to variations in aerosol loading. *Journal of Atmospheric Science* 71: 2581–2603.

Small JD, Chuang PY, Feingold G, Jiang H. 2009. Can aerosol decrease cloud lifetime? *Geophysical Research Letters* 36: L16806.

Tas E, Teller A, Altaratz O, Axisa D, Bruintjes R, Levin Z, Koren I. 2015. The relative dispersion of cloud droplets: its robustness with respect to key cloud properties. *Atmospheric Chemistry and Physics* 15: 2009–2017.

Tölle MH, Krueger SK. 2014. Effects of entrainment and mixing on droplet size distributions in warm cumulus clouds. *Journal of Advances in Modeling Earth Systems* 6: 281–299, doi: 10.1002/2012MS000209.

Twomey S. 1974. Pollution and planetary albedo. *Atmospheric Environment* 8: 1251–1256.