Cloud microphysical relationships and their implication on entrainment and mixing processes in stratocumulus clouds

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Introduction

- Warm rain initiation problem has been known for several decades but solution to this problem is not completely resolved.

- Among several potential solution to this problem is “entrainment and mixing” that leads to the growth of so called “superadiabatic” droplets.

- In this study we examine cloud microphysical relationships of the clouds measured during several aircraft measurement campaigns to find the implication of such relationships on entrainment and mixing process.

- Does entrainment and mixing promote droplet growth? Maybe not!
Condensational droplet growth equation

\[
 r \frac{dr}{dt} = \frac{S - 1}{\left[ \left( \frac{L}{R_vT} - 1 \right) \frac{LQ_L}{KT} + \frac{q_L R_v T}{De_s(T)} \right]} \equiv \frac{S - 1}{[F_k + F_d]}
\]

When solute and curvature effects are included, can only be solved numerically!!

\[
 r \frac{dr}{dt} = \frac{(S - 1) - a + \frac{b}{r^3}}{[F_k + F_d]}
\]

\( F_k \) and \( F_d \) depend on \( T \) and \( p \). \( L, K \) and \( e_s(T) \) are dominantly dependent on \( T \) but \( D \) is dependent on both \( T \) and \( p \).

The condensational growth parameter \( \xi_1 \) can be defined:

\[
 \xi_1 = \frac{1}{F_k + F_d}.
\]
For the same $S$, droplet growth is faster at higher $T$ and lower $p$ (equivalently higher $z$).

**FIG. 7.1.** Dependence of the growth parameter $\xi_1 = 1/[F_k + F_d]$ on temperature and pressure. Contours are plotted of the quantity $\log_{10} \xi_1$, with $\xi_1$ expressed in units of $\mu m^2/s$. Dashed lines represent pseudoadiabats corresponding to $\theta_w = 0^\circ C$ and $20^\circ C$. 

Rogers and Yau (1989)
TABLE 7.2. Rate of Growth of Droplets by Condensation (initial radius 0.75 μm). (From Mason, 1971)

<table>
<thead>
<tr>
<th>Nuclear mass (g)</th>
<th>$10^{-14}$</th>
<th>$10^{-13}$</th>
<th>$10^{-12}$</th>
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</thead>
<tbody>
<tr>
<td>Radius (μm)</td>
<td></td>
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</tr>
<tr>
<td>1</td>
<td>2.4</td>
<td>0.15</td>
<td>0.013</td>
</tr>
<tr>
<td>2</td>
<td>130</td>
<td>7.0</td>
<td>0.61</td>
</tr>
<tr>
<td>4</td>
<td>1,000</td>
<td>320</td>
<td>62</td>
</tr>
<tr>
<td>10</td>
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<tr>
<td>20</td>
<td>8,500</td>
<td>7,400</td>
<td>5,900</td>
</tr>
<tr>
<td>30</td>
<td>17,500</td>
<td>16,000</td>
<td>14,500</td>
</tr>
<tr>
<td>50</td>
<td>44,500</td>
<td>43,500</td>
<td>41,500</td>
</tr>
</tbody>
</table>

S - 1 = 0.05%
p = 90 kPa
T = 273 K
Nucleus: NaCl

Rogers and Yau (1989)
When $r$ is sufficiently large, neglect solute and curvature terms. Then,

$$r \frac{dr}{dt} \sim \xi, \text{ where } \xi = (S - 1) /[F_k + F_d].$$

Two very important aspects of condensational droplet growth:

$$r(t) = \sqrt{r_0^2 + 2\xi t},$$

$$r_2(t) - r_1(t) = \frac{r_2^2(0) - r_1^2(0)}{r_2(t) + r_1(t)},$$

Rogers and Yau (1989)
-The growth of droplet populations

Droplets interact with their environment and with each other ➔ affect the droplet sizes and concentrations

Saturation ratio controls the growth of droplet population.

\[
\frac{dS}{dt} = P - C = Q_1 \frac{dz}{dt} - Q_2 \frac{d\chi}{dt},
\]

Increase of S due to cooling in adiabatic ascent

Decrease of S due to condensational loss of vapor

\[
Q_1 = \frac{1}{T} \left[ \frac{\epsilon Lg}{R' c_p T} - \frac{g}{R'} \right]
\]

\[
Q_2 = \epsilon \left[ \frac{R'T}{\epsilon e_s} + \frac{\epsilon L^2}{\rho T c_p} \right].
\]

P: can be derived with the assumption that no loss of moisture by condensation during ascent. That is, water vapor mixing ratio does not vary.

C: can be calculated with similar assumption (i.e., condensation but no ascent)

Rogers and Yau (1989)
$U = 15 \text{ cm s}^{-1}$, CCN of NaCl with moderate conc. (initial $T$ is not given)

\[
\frac{dS}{dt} = P - C
\]

\[
r \frac{dr}{dt} = \frac{(S - 1) - \frac{a}{r} + \frac{b}{r^3}}{[F_k + F_d]}
\]

Rogers and Yau (1989)

**FIG. 7.3.** Initial formation of cloud droplets and the variation of supersaturation above cloud base. (Adapted from Mordy, 1959.)
$N_{CCN}(SS) = C(SS)^k$, $C = 650 \text{ cm}^{-3}$, $k=0.7$, $U = 0.5$ and 2.0 m s$^{-1}$

larger $U \rightarrow$ higher SS  
higher SS $\rightarrow$ higher N  
larger $U \rightarrow$ higher N  
$\rightarrow$ smaller $r$ for similar LWC  
larger $U \rightarrow$ shorter growth time to reach the same h  
$\rightarrow$ slightly smaller LWC

FIG. 7.4. Early development of cloud properties in air ascending at constant velocity of 0.5 m/s or 2 m/s.

Rogers and Yau (1989)
Usually observed droplet spectrum broadens as droplets grow with altitude!!!

**Fig. 2.** Standard deviation ($\sigma_c$) and mean diameter (MD) of the droplet spectrum from the FSSP ($d < 50 \ \mu m$) averaged for each of the NCAR Electra vertical soundings in ASTEX: $A$ and $B$ are the slope and intercept of the linear regression, $\Gamma$ is the correlation coefficient, and $n$ is the number of data points.

Hudson and Yum (1997)
Comparison of theoretical prediction at 200 m from cloud base and observation from horizontal penetration

Yum and Hudson (2005)
**Giant nuclei:** equil. size of giant soluble (deliquesced) particles may exceed $r$ of 20 $\mu$m. ex) NaCl particles of $SS_c=0.002\%$ has $r_s=1.4$ $\mu$m and equil. radius at RH=100% is $r_e=21$ $\mu$m. Insoluble particle of $r > 20$ $\mu$m can also be involved in coalescence process immediately.

**Entrainment and Mixing**
- Homogeneous mixing
- Inhomogeneous mixing
- Entity mixing

**Turbulence enhanced broadening during condensational growth**
(i.e., stochastic condensational growth)

**Turbulence enhanced collision**
MIXING SCENARIOS

Homogeneous mixing (HM): when $\tau_e >> \tau_m$
All droplets in the mixed parcel experience the same degree of evaporation.

Inhomogeneous mixing (IM): when $\tau_e << \tau_m$
Droplets of the cloudy air adjacent to entrained air completely evaporate while the droplets in the remaining portion experience no evaporation.

$\tau_e$ : time for complete evaporation of a droplet

$$\tau_e = \frac{-D^2(F_k + F_d)}{8(S - 1)}$$

$\tau_m$ : time for complete homogenization of a mixed parcel

$$\tau_m = \left(\frac{l_E^2}{\varepsilon}\right)^{1/3}$$
Homogeneous mixing (HM)

Inhomogeneous mixing (IM)
Effect of entrainment and mixing on cloud microphysics can be expressed as relative deviation from the adiabatic values.

\[ L = \frac{\pi ND_v^3}{6} = NV \]
\[ L_a = \frac{\pi N_a D_{va}^3}{6} = N_a V_a \]
\[ \alpha = \frac{L}{L_a} = \frac{N}{N_a}\left(\frac{D_v^3}{D_{va}^3}\right) = \frac{N}{N_a}\left(\frac{V}{V_a}\right) \]

**L:** cloud droplet liquid water content (LWC)
**N:** cloud droplet number concentration
**\(D_v\):** volume mean mean diameter of cloud droplets (\(\pi D_v^3/6 = V\))
**\(L_a, N_a, D_{va}\) and \(V_a\):** adiabatic values of L, N, \(D_v\) and V
**\(\alpha\):** LWC dilution ratio

**HM:** N decreases due to dilution and V decreases due to evaporation

**IM:** N decreases due to both dilution and complete evaporation of some of the droplets but V remains constant
\[ \alpha = \frac{L}{L_a} = \frac{NV}{N_a V_a} = \frac{(N/N_a)(V/V_a)}{xy}. \] So \( y = \alpha/x \) for a constant value of \( \alpha \)

Limitation

Difficult to find the adiabatic values \( (N_a \text{ and } V_a) \) for a cloud segment since even for adiabatic clouds, they can vary if updraft speed is not uniform.

Shows only a snapshot of cloud microphysical relationships at the moment of measurement

(Burnet and Brenguier, 2007)
Fig. 8. Scatterplot of $N - D_e^3$ for in situ–measured MVD and CDNC for the three cases. Isocontours of the frequency distribution are drawn for levels corresponding to 25%, 50%, 75%, and 90% of the data.

$\tau_e / \tau_m = 6.6$

$\tau_e / \tau_m = 0.05$

$\tau_e / \tau_m : 1/D_a$
(D_a: Damkohler number)

Burnet and Brenguier (2007)
VAMOS (Variability of the American Monsoon System) Ocean Cloud Atmosphere Land Study

Yum et al. (2015)

Oct.-Nov., 2008
The time variation of important cloud variables (O28)
The vertical profiles of thermodynamic variables and L (O28)
Mixing diagram (1 Hz)

• Difficult to interpret!!

• Relative dispersion, $\xi$, generally increases as $\alpha$ decreases.
Frequently observed types of mixing diagram from O26 and O28
(20 s segments of 40 Hz data scatterplot and $\alpha$ bin plot)
Expected correlations for some dominant cloud microphysical processes.

<table>
<thead>
<tr>
<th>Dominant Process</th>
<th>$\Gamma_{N,V}$</th>
<th>$\Gamma_{N,L}$</th>
<th>$\Gamma_{V,L}$</th>
<th>No. of Segments</th>
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<tbody>
<tr>
<td>HM</td>
<td>$&gt; 0$</td>
<td>$&gt; 0$</td>
<td>$&gt; 0$</td>
<td>47</td>
</tr>
<tr>
<td>IM</td>
<td>$\sim 0$</td>
<td>$&gt; 0$</td>
<td>$\sim 0$</td>
<td>0</td>
</tr>
<tr>
<td>Further growth after IM</td>
<td>$&lt; 0$</td>
<td>$&gt; 0$</td>
<td>$&lt; 0$</td>
<td>10</td>
</tr>
<tr>
<td>Many recently activated droplets</td>
<td>$&lt; 0$</td>
<td>$&lt; 0$</td>
<td>$&gt; 0$</td>
<td>43</td>
</tr>
<tr>
<td>Small variation of $L$</td>
<td>$&lt; 0$</td>
<td>$&gt; 0$</td>
<td>$&gt; 0$</td>
<td>169</td>
</tr>
<tr>
<td>Not classified</td>
<td>$\cdot$</td>
<td>$\cdot$</td>
<td>$\cdot$</td>
<td>34</td>
</tr>
</tbody>
</table>

The dot in “not classified” indicates no preference for the sign of correlation coefficient.

- There are 47 segments that suggest HM.
- **No segment satisfies the criteria for IM**, but there are 10 segments that support further growth after IM.
- Small variation of $L$ is the most frequently found cases.
- Important thing to note is that **positive relationship between $V$ and $L$** is dominant for most of cloud segments.
Transition length scale ($J^*$) and transition scale number ($J_L$)

- $J^*$ indicates the length scale when the Damköhler number becomes 1 (Lehmann et al., 2009).
  \[ J^* = \varepsilon^2 \tau_r^2 \]

- $J_L$ is the transition scale number, the ratio of $J^*$ to the Kolmogorov length scale ($\eta$) (Lu et al., 2011).
  \[ J_L = \frac{J^*}{\eta} \]

- The transition length and number strongly suggest IM for VOCALS clouds.
Correlation Coefficients between cloud microphysical variables

Unlike all other penetrations, P1 of O17 was close to cloud top!

<table>
<thead>
<tr>
<th></th>
<th>( \Gamma_{N-V} )</th>
<th>( \Gamma_{N-L} )</th>
<th>( \Gamma_{V-L} )</th>
<th>( \Gamma_{N-V} )</th>
<th>( \Gamma_{N-L} )</th>
<th>( \Gamma_{V-L} )</th>
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<tr>
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<tr>
<td>P1</td>
<td>[0.35 \pm 0.40]</td>
<td>[0.88 \pm 0.10]</td>
<td>[0.04 \pm 0.38]</td>
<td>[-0.48]</td>
<td>[0.91]</td>
<td>[-0.09]</td>
</tr>
<tr>
<td>P2</td>
<td>[-0.51 \pm 0.30]</td>
<td>[0.03 \pm 0.47]</td>
<td>[0.76 \pm 0.28]</td>
<td>[-0.33]</td>
<td>[0.21]</td>
<td>[0.84]</td>
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<td>O26</td>
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</tr>
<tr>
<td>P1</td>
<td>[-0.14 \pm 0.19]</td>
<td>[-0.10 \pm 0.32]</td>
<td>[0.18 \pm 0.16]</td>
<td>[0.26 \pm 0.36]</td>
<td>[0.91 \pm 0.11]</td>
<td>[0.90 \pm 0.11]</td>
</tr>
<tr>
<td>P2</td>
<td>[-0.15 \pm 0.22]</td>
<td>[-0.09 \pm 0.28]</td>
<td>[0.48 \pm 0.26]</td>
<td>[0.59 \pm 0.29]</td>
<td>[0.74 \pm 0.15]</td>
<td>[0.69 \pm 0.18]</td>
</tr>
<tr>
<td>P3</td>
<td>[-0.21 \pm 0.32]</td>
<td>[-0.10 \pm 0.30]</td>
<td>[0.66 \pm 0.15]</td>
<td>[0.73 \pm 0.18]</td>
<td>[0.53 \pm 0.16]</td>
<td>[0.55 \pm 0.19]</td>
</tr>
<tr>
<td>P4</td>
<td>[-0.62 \pm 0.05]</td>
<td>[-0.35 \pm 0.28]</td>
<td>[-0.11 \pm 0.11]</td>
<td>[-0.13 \pm 0.33]</td>
<td>[0.82 \pm 0.03]</td>
<td>[0.79 \pm 0.21]</td>
</tr>
<tr>
<td>O28</td>
<td></td>
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<tr>
<td>P1</td>
<td>[-0.30 \pm 0.22]</td>
<td>[-0.12 \pm 0.27]</td>
<td>[0.48 \pm 0.27]</td>
<td>[0.60 \pm 0.23]</td>
<td>[0.65 \pm 0.09]</td>
<td>[0.68 \pm 0.16]</td>
</tr>
<tr>
<td>P2-1</td>
<td>[-0.29 \pm 0.27]</td>
<td>[-0.16 \pm 0.37]</td>
<td>[0.34 \pm 0.29]</td>
<td>[0.46 \pm 0.38]</td>
<td>[0.73 \pm 0.08]</td>
<td>[0.72 \pm 0.17]</td>
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<tr>
<td>P2-2</td>
<td>[-0.22 \pm 0.35]</td>
<td>[-0.17 \pm 0.36]</td>
<td>[0.55 \pm 0.20]</td>
<td>[0.57 \pm 0.28]</td>
<td>[0.61 \pm 0.14]</td>
<td>[0.64 \pm 0.21]</td>
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<tr>
<td>P3</td>
<td>[-0.13 \pm 0.17]</td>
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<td>[0.64 \pm 0.17]</td>
<td>[0.70 \pm 0.20]</td>
<td>[0.63 \pm 0.14]</td>
<td>[0.63 \pm 0.17]</td>
</tr>
<tr>
<td>P4-1</td>
<td>[0.06 \pm 0.30]</td>
<td>[0.05 \pm 0.34]</td>
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<td>[0.54 \pm 0.16]</td>
<td>[0.57 \pm 0.21]</td>
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<tr>
<td>P4-2</td>
<td>[-0.03 \pm 0.27]</td>
<td>[-0.06 \pm 0.26]</td>
<td>[0.78 \pm 0.08]</td>
<td>[0.80 \pm 0.12]</td>
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</tr>
<tr>
<td>P5</td>
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<td>[0.02 \pm 0.22]</td>
<td>[0.84 \pm 0.10]</td>
<td>[0.86 \pm 0.09]</td>
<td>[0.53 \pm 0.09]</td>
<td>[0.49 \pm 0.19]</td>
</tr>
<tr>
<td>P6</td>
<td>[-0.18 \pm 0.20]</td>
<td>[-0.06 \pm 0.21]</td>
<td>[0.74 \pm 0.17]</td>
<td>[0.80 \pm 0.12]</td>
<td>[0.48 \pm 0.08]</td>
<td>[0.52 \pm 0.17]</td>
</tr>
</tbody>
</table>
Table 1. Correlation Coefficients Between Aerosol and Cloud Microphysics Calculated From 1 s Data as a Function of Sampling Altitude

<table>
<thead>
<tr>
<th>Flight Date</th>
<th>Altitude (m)</th>
<th>$N_{PCASP}$</th>
<th>$N_D$</th>
<th>$D_{a,n}$</th>
<th>$\sigma_D$</th>
<th>$\gamma$</th>
<th>$LWMR$</th>
<th>$\gamma$</th>
<th>$LWMR$</th>
<th>$\gamma$</th>
<th>$LWMR$</th>
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<th>$LWMR$</th>
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<td>389</td>
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<td>0.71</td>
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<td>187</td>
<td>-0.21</td>
<td>-0.85</td>
<td>0.93</td>
<td>0.90</td>
<td>0.69</td>
<td>-0.39</td>
<td>-0.58</td>
<td>-0.60</td>
<td>0.50</td>
<td>0.49</td>
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<tr>
<td>20 Jul 2005</td>
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<tr>
<td>20 Jul 2005</td>
<td>69</td>
<td>-0.93</td>
<td>0.56</td>
<td>-0.30</td>
<td>-0.73</td>
<td>0.72</td>
<td>0.84</td>
<td>0.20</td>
<td>-0.36</td>
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Figure 11. Modeled evolutions of (a) liquid water mixing ratio, (b) supersaturation, (c) droplet number concentration, (d) mean droplet diameter, (e) standard deviation of droplet diameter, and (f) the diameter of the largest droplet size bin for a LLCL cloud parcel and mixtures of the LLCL and HLCL cloud parcels with volume mixing ratio of 70:30, 50:50, and 30:70. The LLCL cloud parcel has a LCL of 50 m and is mixed with the HLCL parcel at its LCL of 150 m.
Entrainment

\[ \frac{V_a, L_o}{\gamma_{V-L}} \sim 0 \quad \leftarrow \quad V_a, L_{\text{reduced}} = \frac{V_a, L_o}{\gamma_{V-L}} \rightarrow \quad \text{Aircraft penetration} \]

\[ \nabla \text{evaporation} \]

\[ \nabla \text{evaporation} \]

\[ \frac{V_a, L_o}{\gamma_{V-L}} > 0 \]
- Liquid water potential temperature

- Virtual potential temperature

- CTEI criterion was satisfied in these clouds

CTEI criterion: \[ \Delta \theta_e - \kappa \left( \frac{L_v}{C_p} \right) \Delta q_T < 0 \]
Routine AAF Clouds with Low Optical Water Depths (CLOWD) Optical Radiative Observations (RACORO)

January-June, 2009

Yeom et al. (2017)
The differences of $T$ and $T_d$ between in and above the clouds were much smaller compared to the VOCALS maritime stratocumulus clouds (Yum et al., 2015).
Most of the segments show the data scatter similar to those shown in segments 67 and 81 as N/N_m decreases with the decrease of V/V_m, which clearly indicates HM.
Correlation Coefficients

- Basically two patterns emerge dominantly for the 110 cloud segments (HM, Small variation in L).

<table>
<thead>
<tr>
<th>Process</th>
<th>$\Gamma_{N-V}$</th>
<th>$\Gamma_{N-L}$</th>
<th>$\Gamma_{V-L}$</th>
<th>No. of segments</th>
</tr>
</thead>
<tbody>
<tr>
<td>HM</td>
<td>$&gt; 0$</td>
<td>$&gt; 0$</td>
<td>$&gt; 0$</td>
<td>93</td>
</tr>
<tr>
<td>IM</td>
<td>$\sim 0$</td>
<td>$&gt; 0$</td>
<td>$\sim 0$</td>
<td>0</td>
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<tr>
<td>Small variation in L</td>
<td>$&lt; 0$</td>
<td>$&gt; 0$</td>
<td>$&gt; 0$</td>
<td>13</td>
</tr>
<tr>
<td>Not classified</td>
<td>--</td>
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</table>

- These correlation coefficient values strongly support the HM.
The transition length scale ($L^*$) and scale number ($N_L$)

<table>
<thead>
<tr>
<th>Segment number</th>
<th>67</th>
<th>81</th>
<th>31</th>
<th>65</th>
<th>27</th>
<th>84</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean transition scale number ($N_L$)</td>
<td>35.2</td>
<td>33.3</td>
<td>4.7</td>
<td>2.3</td>
<td>4.4</td>
<td>5.3</td>
</tr>
<tr>
<td>Mean transition length ($L^*$) (cm)</td>
<td>7.1</td>
<td>7.8</td>
<td>1.3</td>
<td>0.7</td>
<td>1.4</td>
<td>1.7</td>
</tr>
<tr>
<td>Dominant process</td>
<td>HM</td>
<td>HM</td>
<td>Vaguely HM</td>
<td>Vaguely HM</td>
<td>Iso-α line</td>
<td>Iso-α line</td>
</tr>
</tbody>
</table>
The environment conditions suggest more prevalent occurrence of homogeneous mixing.

Relationship between $W$ and $L$ suggests vertical circulation in most cases but not always.
• The relationship between $\theta_v$ and $L$ does not support vertical circulation hypothesis.

• $\theta_v$ is higher for more diluted parcels, which means that more buoyant parcels tend to descend.

• This contradictory result is suspected to be related to the limitation of humidity ($T_d$) measurement in clouds during the RACORO campaign.
Aerosol and cloud experiments in the eastern north Atlantic (ACE-ENA)

1 June 2017 - 28 February 2018

(Wang et al., 2016)
Example of cloud measurement

- During ACE-ENA campaign, long horizontal penetrations at various altitudes were made.
The relationships between cloud microphysical variables

- Correlation between $L$ and $V$ exhibits **vertical variation**. As altitude goes down, it becomes **more positive**.

- $L$ is positively correlated with $N$ at all altitudes.

- Vague correlation between $N$ and $V$. 
Summary for examined penetrations

<table>
<thead>
<tr>
<th></th>
<th>$\Gamma_{N-L}$</th>
<th>$\Gamma_{N-V}$</th>
<th>$\Gamma_{L-V}$</th>
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<th>$\Gamma_{N-L}$</th>
<th>$\Gamma_{N-V}$</th>
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<td>RF0718-P1</td>
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<tr>
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</tbody>
</table>

- All penetrations show the **same trends**: $\Gamma_{L-V}$ is more positive as altitude goes down.
Mixing diagrams for a 20 s section at several sampling altitudes

- Most cloud segments near cloud top show IM trait.
- Segments at middle and near cloud base suggest HM trait.
The CTEI criterion is satisfied for RF0718 P1 and P2, implying that entrained and mixed parcels can be susceptible to downward movement through the cloud.

\[ \Theta_v \] and L are negatively correlated, which is contradictory to the expectation of negative buoyancy of entrainment affected diluted parcels.

Such contradictory results could be related to the measurement uncertainty of humidity in clouds.
Summary

• Cloud microphysical relationships represented by mixing diagrams and linear correlation coefficients suggested HM for the maritime stratocumulus clouds (VOCALS, ACE-ENA, MASE (Wang et al., 2009)) and more so for continental stratocumulus clouds (RACORO).

• Moreover, evidence for IM or further growth after IM is not easily found. No super-adiabatic droplet growth caused by entrainment and mixing at least for the data presented here!

• Vertical circulation is speculated to be one of the crucial reasons why the HM traits is dominantly shown especially deeper down into the clouds.

• Then what?
  • “entrainment and mixing” is not a good potential mechanism that sets the stage for collision & coalescence.
  • Do the models capture these features? If not, what does it mean?