Effects of Boundary Layer depth, stability, precipitation, and droplet concentration on stratocumulus evolution using a Lagrangian approach

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Subsidence Regions with Abundant Sc

- Regions chosen based on annual average Sc amounts from surface observations
- Chose large boxes to capture Sc maxima and regions of strong gradient (Sc → Cu)
The Lagrangian Approach

- Follow the same 100km-radius sample for 48 hours, observing with every A-Train flyover at 12-hour intervals (~1:30 and ~13:30 local time)
- We use ~62,000 individual trajectories (2007-2008)
The Lagrangian Approach

- Use ERA-Interim u, v wind fields at 925 mb
- Observe initially with CloudSat, CALIPSO, MODIS
- Observe again with MODIS
Data Products

• Cloud Cover from MODIS level 3 cloud mask
  – 1x1 degree lat/lon grid
  – Day and night
  – Release 5

• Lower Tropospheric Stability (LTS)
  – Difference in $\theta$ between 700mb and 2 meters
  – From ERA-Interim reanalysis
Data Products

• Droplet Concentration \((N_d)\) from two MODIS products:
  
  – Effective Radius \((r_e)\), Liquid Water Path (LWP)
  – Daytime only, from Optical Properties dataset
  – \(N_d = N_{\text{eff}}/k\) \((k = 0.8)\) for marine stratiform clouds

\[
N_{\text{eff}} = \sqrt{2} \frac{3}{4} \pi \rho_w \Gamma_{\text{eff}}^2 \frac{1}{r_e(h)^3} \frac{LWP^2}{LWP}
\]
MODIS Droplet Concentration $N_d$
Data Products

- PBL depth from CALIPSO (Eastman and Wood 2016) based on highest cloud tops from VFM
- PBL depth from MODIS using:
  - Temperature contrast between cloud tops (from MODIS cloud top temperature histograms) and reanalysis SST
  - Using parameterized lapse rate from Wood and Bretherton 2004 (Figure 4)
All Lagrangian Variables converted to Anomalies

• All variables tracked in this Lagrangian study are anomalies:
  – Diurnal cycle removed
  – Seasonal cycle removed

• This was necessary to avoid any geographic biases produced by uneven trajectory distances and distributions
Zenith Angle Bias

• The wide sensor viewing angle on MODIS (~67°) makes a zenith angle bias likely
  – Bias was observed in cloud cover, effective radius and LWP
  – Bias is removed from all data using the polynomial fits shown
Red Noise Considerations

- Cloud Cover Anomalies (CCA) tend to regress to the mean (anomaly = 0)
- Linear relationship between CCA and $\Delta$CCA shows $\Delta$CCA to partially be a linear function of CCA
- Is well modeled as a red noise process

$$\Delta CCA = \Delta CCA(CCA_{T=0}) + \Delta CCA(\text{Environment})$$
Red Noise Considerations

- We calculate the slope between CCA and \( \Delta \text{CCA} \)
- Remove the \( \Delta \text{CCA} \) that is a function of CCA\((T=0)\) to produce a “Residual \( \Delta \text{CCA} \)”, which is a function of the surrounding environment

\[ \text{Residual } \Delta \text{CCA} = \Delta \text{CCA} - \Delta \text{CCA}(\text{CCA}_{T=0}) \]

\[ = \Delta \text{CCA}(\text{Environment}) \]
Stability and Cloud Cover

- High stability associated with longer-lived clouds
- Low stability associated with cloud breakup
PBL Depth and Cloud Cover

- Clouds in shallow boundary layers persist.
- Clouds in deeper boundary layers tend to break up more quickly.

![Graph showing the relationship between PBL depth and residual CCA](graph.png)
Correlation among Variables

- Low stability is associated with deeper PBLs  
  \[ r = -0.20 \]

- Need a method to untangle which variable drives cloud breakup
PBL Depth, Stability, and Cloud Cover

- When we control for PBL depth, LTS still shows a clear effect
- Clouds in less stable environments tend to break up
PBL Depth, Stability, and Cloud Cover

- When we control for LTS, PBL depth also still shows an effect.
- Clouds in deep boundary layers tend to break up regardless of LTS.
Rain, PBL Depth, and Cloud Cover

• When we control for PBL depth, rain shows minimal effects.

• Since rain occurs preferentially in deep PBLs, failure to account for this would produce spurious results.

<table>
<thead>
<tr>
<th>PBL Depth</th>
<th>Residual ΔCCA0-24 (%)</th>
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</thead>
<tbody>
<tr>
<td>1km</td>
<td></td>
</tr>
<tr>
<td>1.5km</td>
<td></td>
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<tr>
<td>2km</td>
<td></td>
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<tr>
<td>2.5km</td>
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</tbody>
</table>

![Graph showing residual ΔCCA0-24 (%) vs PBL Depth for Pcp = 0 mm/hr and Pcp > 0.]
Rain, PBL Depth, and Cloud Cover

- Changing the rain rate threshold hints at a possible precipitation effect
  - In shallow PBLs, heavy rain is associated with persistent clouds
  - Possibly an effect rather than a cause?
  - Stronger well-mixed circulations could produce more rain
PBL Depth, Rain and Droplet Concentration

- Rain appears to affect $N_d$ in shallow PBLs much more than deep
  - Deep PBLs tend to lose $N_d$ regardless of precipitation
  - Shallow PBLs with no precip tend to sustain greater droplet concentration
Rain, Stability, and PBL deepening

- The PBL appears to deepen more readily with lower LTS:
  - Less entrainment of dry, warm air with high stability

- Precipitating PBLs deepen less than dry ones for strong and weak LTS
Conclusions

• Lagrangian studies of this magnitude require careful consideration of instrument biases and red noise processes

• We support many prior results and assumptions about cloud breakup, with cloud breakup more prevalent in deep PBLs and with lower LTS
  – Effects appear independently
  – Effects of rain are more subtle, and may depend upon PBL

• The effect of rain on $N_d$ is dependent on PBL depth

• Changes in PBL depth are likely affected by LTS and precipitation processes
  – PBL deepens more with lower LTS
  – PBL deepens less with precipitation