LES Intercomparison of Drizzling Stratocumulus: DYCOMS-II RF02

Andy Ackerman, NASA Ames Research Center
http://sky.arc.nasa.gov:6996/ack/gcss9

Acknowledgments
Magreet van Zanten, KNMI
Bjorn Stevens, UCLA
Markus Petters, CSU
Participating Groups
Outline

• Motivation

• Case specifications

• Some results (ensemble, then group by group)
  o time series
  o profiles
  o trends within ensemble

• Summary

• Questions and issues
Scientific Focus

- How do increasing numbers of submicron aerosol affect stratocumulus
  - cloud cover
  - liquid water path
- How does drizzle affect
  - boundary layer dynamics
  - entrainment
  - bulk cloud properties
- How do predictions of drizzle in LES compare with observations?
- Does sedimentation of cloud droplets affect results?
- If so, is the response from different models consistent?
Results from Previous Workshop

- Case: DYCOMS-II RF01, with very dry inversion, droplet concentrations about $100 \text{ cm}^{-3}$, and no precipitation below cloud base

- Most LES entrained overlying air faster than measurements indicated, resulting in a thin, cloud layer with LWP lower than observed

- Reduction of radiative cooling by thin clouds results in poorly mixed boundary layers $\Rightarrow$ negative feedback on further entrainment

- Limiting subgrid-scale mixing at inversion (ad hoc or by skill or luck of SGS model) reduces entrainment, resulting in well-mixed boundary layer with thick cloud layer
Drizzle and Entrainment in a Mixed Layer Model

Steady–state moisture budget:
\[ \text{sfc source} = \text{entrainment drying} + \text{precipitation} \]

- Decreased drizzle leads to deeper boundary layer and thicker cloud \textit{(Pincus & Baker 1994)}
- Considered a single meteorological scenario, with a moist inversion
- Whether entrainment deepens or thins a cloud layer depends on thermodynamic jumps at top of BL \textit{(Randall 1984)}
Large-Eddy Simulations of Strongly Precipitating, Shallow, Stratocumulus-Topped Boundary Layers (Stevens et al. 1998)

- ASTEX case study (moist inversion) with CCN concentration of $25 \text{ cm}^{-3}$, using bin microphysics and 2-stream radiative transfer

- Drizzle dries updrafts $\Rightarrow$ less evaporative cooling available to drive downdrafts

- Dry downdrafts $\Rightarrow$ cumuliform convection (Bjerknes 1938)

- “Moreover, light drizzle – by reducing entrainment in PBLs with large jumps in moisture across the inversion – might actually lessen entrainment drying thereby leading to deeper PBL clouds. Such scenarios are largely speculative and need to be considered further.”
The Impact of Humidity above Stratiform Clouds on Indirect Aerosol Climate Forcing (Ackerman et al. 2004)

- LES with bin microphysics and 2-stream radiative transfer based on three case studies: ASTEX (A209, 4th GCSS WG1 Workshop), FIRE-I (EUROCS intercomparison), and DYCOMS-II (RF01, 8th GCSS WG1 Workshop)

- Droplet sedimentation and drizzle consistently decrease with increasing numbers of sub-micron aerosol

- Entrainment consistently increases as water sedimentation decreases

- Response of LWP depends on humidity of air overlying boundary layer
Temperature and Moisture Jumps above Cloud Top

![Graph showing temperature and moisture jumps above cloud top with data points for ASTEX, FIRE-I, and RF01]
Domain Averages

Liquid Water Path (g m\(^{-2}\)) vs. Droplet Concentration (cm\(^{-3}\))

- ASTEX (solid blue line)
- FIRE-I (dotted cyan line)
- dry ASTEX (dashed green line)
- DYCOMS-II (solid red line)
Response to Suppressing Water Sedimentation

![Graphs showing the response of ASTEX and RF01 to suppressing water sedimentation.](image-url)
Temperature and Moisture Jumps above Cloud Top

- Temperature change $\Delta \theta$ (K)
- Moisture change $\Delta q_t$ (g/kg)

- RF01: 35 cm$^{-3}$
- RF02: 35 cm$^{-3}$
- FIRE-I: 225 cm$^{-3}$
- ASTEX: >350 cm$^{-3}$
Model Domain

- Wider than past GCSS stratocumulus domains to allow for larger scales of convective organization expected in drizzling regime:
  
  \[ 6.4 \times 6.4 \times 1.5 \text{ km}, \Delta x = \Delta y = 50 \text{ m}, \Delta z = 5 \text{ m} \text{ near surface and initial inversion} \]

- Those able to use a stretched grid requested to use specified grid, with 96 layers
Initial Conditions and Forcings

- Radiation: Beer’s Law parameterization from previous workshop, which includes heating at cloud base, cooling at and above cloud top (no hook for radiative term in droplet condensational growth equation)

- Subsidence: fixed divergence of horizontal wind \((3.76 \times 10^{-6} \text{ s}^{-1})\)

- Coriolis: geostrophic wind profiles specified (by Bjorn)

- Surface fluxes: fix friction velocity at 0.28 m/s, surface Prandtl number at unity, surface temperature at 292 K, and 100% RH at surface (should be 98% because of salinity)

- Sponge: above 1250 m with time constant of 100 s
Cloud Microphysics

- Leg averages of droplet number concentrations \( (N, \text{cm}^{-3}) \) within cloudy air (defined by \( N > 20 \text{ cm}^{-3} \)):

<table>
<thead>
<tr>
<th>Flight Leg</th>
<th>Open Cells</th>
<th>Closed Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud Top</td>
<td>54 ± 14</td>
<td>60 ± 13</td>
</tr>
<tr>
<td>Cloud Base</td>
<td>56 ± 16</td>
<td>80 ± 17</td>
</tr>
</tbody>
</table>

- Fix \( N \) at 65 cm\(^{-3}\), if possible

- If microphysics ignores sedimentation of cloud droplets, use integral over log-normal size distribution assuming Stokes sedimentation \( (v \sim r^2) \):

\[
F = c \left( \frac{3}{4\pi N} \right)^{2/3} q_l^{5/3} \exp(5 \ln^2 \sigma_g)
\]

where \( c \) is taken from Rogers and Yau (1989) and \( \sigma_g = 1.5 \)

- If unable to fix \( N \), use idealized CCN spectrum based on measurements
Cloud Condensation Nuclei

Within BL

- Using non-prognostic aerosol, cannot handle vertical variation in context of a BL that is deepening

Above BL

- Dotted line is idealized bimodal fit for BL aerosol assuming ammonium bisulfate (log-normal, not a power law)

- Supersaturation for droplet activation specified to not exceed 1% during first hour
## Model Descriptions

<table>
<thead>
<tr>
<th>Group/Model Team</th>
<th>SGS Model</th>
<th>Precipitation Microphysics</th>
<th>Cloud Droplet Sedimentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSU/RAMS</td>
<td>Deardorff</td>
<td>2 moment</td>
<td>some</td>
</tr>
<tr>
<td>Jiang</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSU/SAM</td>
<td>Deardorff</td>
<td>Khairoutdinov and Kogan</td>
<td>yes</td>
</tr>
<tr>
<td>Khairoutdinov</td>
<td></td>
<td>(2 moment)</td>
<td></td>
</tr>
<tr>
<td>MetO</td>
<td>Smag-Lilly</td>
<td>2 moment</td>
<td>yes</td>
</tr>
<tr>
<td>Lock</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MPI</td>
<td>Deardorff</td>
<td>1 moment, 2 moment</td>
<td>no</td>
</tr>
<tr>
<td>Chlond</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NASA/DHARMA Ackerman</td>
<td>dynamic</td>
<td>bin, Wyant et al. (2 moment)</td>
<td>yes</td>
</tr>
<tr>
<td>NRL/COAMPS Golaz</td>
<td>Deardorff</td>
<td>Khairoutdinov and Kogan</td>
<td></td>
</tr>
<tr>
<td>U Redding/LEM Weinbrecht</td>
<td>Smag-Lilly</td>
<td>1 moment</td>
<td>no</td>
</tr>
<tr>
<td>UCLA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Savic-Jovcic, Stevens</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U Utah</td>
<td>Deardorff</td>
<td>1 moment?</td>
<td>yes</td>
</tr>
<tr>
<td>Zulauf, Krueger</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Utrecht-KNMI/DALES van Zanten, de Roode</td>
<td>Deardorff</td>
<td>none</td>
<td>yes</td>
</tr>
<tr>
<td>WVU</td>
<td>Deardorff</td>
<td>Khairoutdinov and Kogan</td>
<td>yes</td>
</tr>
<tr>
<td>Lewellen</td>
<td>w/ partial cloudiness</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Ensemble Requirements

- One simulation from each group w/ and w/o precipitation
- Precipitation must include warm rain or drizzle, not just cloud droplet sedimentation, and no sedimentation permitted in run w/o precipitation
- Specification must be followed for both simulations
- Nine groups satisfied these constraints:
  - CSU (Khairoutdinov), MetO, MPI, NASA, NCAR, NRL, U Reading, U Utah, WVU
- Results from 13 groups shown here, just not included in ensemble
- A bit low on LWP and high on entrainment
- Nowhere near enough drizzle, and vapor flux too large
- Drizzle decreases entrainment, convective velocity scale (integral of buoyancy flux), and surface vapor flux, but not LWP median
Includes “giant” CCN, substantially suppressing droplet activation
LWP nearly triples in response to light drizzle, and cloud cover increases
• LWP roughly doubles in response to cloud droplet sedimentation alone slightly decreases when drizzle is then included, and then increases when droplet concentrations reduced by 25%
- Variable mixing length in SGS model diminishes entrainment and doubles LWP; monotone advection of scalars furthers both trends
• Thick, overcast cloud is not maintained (w/ and w/o drizzle)
• Entrainment slows as radiative cooling diminishes
• One-parameter (Kessler) drizzle scheme has little effect; two-parameter scheme further diminishes LWP and cloud cover
• LWP increases (too much) with bin microphysics (lack radiative effect on droplet growth)
• Precipitation (brackets measurements when parameterized) reduces entrainment too much
• CCN in boundary layer not enough to maintain measured droplet concentration
Precipitation nearly as great as measured, substantially reduces LWP and cloud cover
- Precipitation reduces LWP
- Precipitating simulation is archetypical ensemble member
- Precipitation limited to cloud droplet sedimentation, which increases entrainment and decreases LWP
- Precipitation has little effect
- Turning of stochastic backscatter (negative viscosity) increases LWP and cloud cover
- Precipitation w/o cloud droplet sedimentation has little effect
- Precipitation w/ cloud droplet sedimentation decreases entrainment and increases LWP
• Thick, overcast cloud is not maintained (w/ and w/o drizzle)
• Cloud droplet sedimentation (not drizzle) decreases LWP and cloud cover
• Precipitation w/o cloud droplet sedimentation has little effect
• Precipitation w/ cloud droplet sedimentation decreases entrainment and increases LWP
• Particularly narrow dispersion and range of precipitation
- Dispersion low
- Peak values more than 50 standard deviations from mean

⇒ Precipitation limited to very small area
• Geostrophic wind speeds too high, and total fluxes far from measurements
• Median precipitation remarkably similar to average in closed cells
• Mistakenly included an extra member in ensemble for these profiles, but precipitation-induced changes in total moisture flux seems inconsistent with other results, suggesting possible internal inconsistencies in ensemble member(s)
Precipitation diminishes buoyancy flux and decreases $\overline{w'^2}$, and increases $\overline{w'^3}$ (away from observations). Precipitation diminishes buoyancy flux and decreases $\overline{w'^2}$, allowing for more vigorous convection by decreasing entrainment through diminished surface fluxes and kinetic energy (?). Momentum flux disagreement suggests scales beyond extent of model domain.
Response to Droplet Sedimentation

CSU_Marat

DHRAMA

Utah
For all but UCLA, droplet sedimentation results in reduced entrainment and increased LWP, consistent with Ackerman et al. (2004)
• Precipitation generally increases with LWP, as expected
• NCAR is exception to trend (LWP low and precipitation high)
• Should compare cloud base precipitation trend to $H^3 N$ scaling found by Pawloska and Brenguier (2003) and van Zanten and Stevens (2005)
- At low LWP, entrainment tends to increase with LWP (radiative cooling)
- Tendency reverses at higher LWP (entrainment drying)
- Should consider more sophisticated analysis along the lines done by Bjorn for previous workshop
Entrainment tends to decreases as precipitation increases.
• The greater LWP is (well-mixed, radiatively driven stratocumulus), the more it tends to increase when precipitation is turned on
• X-axis was meant to be LWP w/o precipitation, but I mistakenly used LWP w/ precipitation instead
Summary

• Precipitation generally reduces $w'\theta_v$, $w'^2$, and entrainment, and increases $w'^3$

• Precipitation leads to increases in LWP and cloud cover in some, and decreases in other simulations; ensemble medians of both are unchanged

• Cloud droplet sedimentation generally decreases entrainment and increases LWP

• Tendencies within ensemble hold promise and require deeper thought and analysis

• Any robustness of tendencies should not be considered universal to stratocumulus, since response of BL dynamics and cloud properties to precipitation depends strongly on thermodynamic jumps above BL

• I am deeply grateful for the efforts of all the participants and those providing measurement analyses
Questions and Issues

- Fix geostrophic winds
- For models that don’t fix droplet number, scale accumulation-mode number concentration to give average cloud droplet number concentration of $\sim 65 \text{ cm}^{-3}$?
- While (if) changing the specification, might as well set RH at surface to 98%
- Any disagreement regarding 3-h averaging period?
- Should variations on grid stretching be permitted?
- If not, should we use WVU’s grid above initial inversion?
- Assess significance of neglecting radiative term in droplet condensational growth