Multi-Scale Modeling of Fine-Scale Structure in Cumulus Clouds

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Motivation

• Our overall goal is to use the Explicit Mixing Parcel Model (EMPM) with droplet growth to study the relative importance of several physical mechanisms that have been proposed to explain droplet spectral broadening and rain initiation in warm cumulus clouds.

• The mechanisms that we are investigating are

  - entrainment and mixing,
  - droplet clustering due to turbulence, and
  - ultragiant cloud condensation nuclei.
Explicit Mixing Parcel Model (EMPM)

• The EMPM predicts the evolving in-cloud variability due to entrainment and finite-rate turbulent mixing using a 1D representation of a rising cloudy parcel.

• The 1D formulation allows the model to resolve fine-scale variability down to the smallest turbulent scales (\(\sim 1\) mm).

• The EMPM can calculate the growth of several thousand individual cloud droplets based on each droplet's local environment.
Scales of Atmospheric Motion

- 10,000 km: Planetary waves
- 1000 km: Extratropical Cyclones
- 100 km: Mesoscale Convective Systems
- 10 km: Cumulonimbus clouds
- 1 km: Cumulus clouds
- 100 m: Turbulence

- 1 m
- 10 m
- 100 m
- 10 mm
- 1 mm

- Global Climate Model (GCM)
- Cloud System Resolving Model (CSRM)
- Large Eddy Simulation (LES) Model

EMPM
The special resolution is adequate to resolve the Kolmogorov scales in the downstream half of the photograph. The Reynolds number is approximately 2000, and the fluorescent jet of water directed downward shows the concentration of fluorescent tracer in the plane of flow.
linear eddy simulations of mixing in homogeneous turbulence, see McMurtry et al. (1993).

The example just described demonstrates the relationship between the entrained blob size and the subsequent scalar variance evolution. In cumulus clouds, variance is produced by multiple entrainment events. The in-cloud variance level is thus determined by the relative rates of variance production by entrainment and variance decay by mixing.

c. EMPM implementation

By combining the linear eddy model described in section 3b with the entrainment parameterization described in section 3a, the EMPM is able to represent the effects of entrainment, turbulent deformation, and molecular diffusion on the internal structure of the parcel.

The evolution of a parcel as it ascends from cloud base is calculated using the EMPM as shown schematically in Fig. 3. The EMPM’s 1D scalar fields are initially uniform and set equal to the observed horizontally averaged cloud base values. As the parcel rises above cloud base at a specified rate based on observations, entrainment events occur at irregular intervals. The entrained blobs are mixed by the linear eddy model’s rearrangement events—which increase the scalar gradients—and by eddy diffusion.

Many realizations (independent calculations) of parcel evolution are made with the EMPM for each set of parcel parameters in order to provide a precise statistical representation of the entrainment and mixing processes, which are both modeled as stochastic processes in the EMPM. Each realization differs from the others in the ensemble in its sequence of entrainment intervals and its set of rearrangement events. Each simulation described in the next section consisted of an ensemble of 100 realizations.

4. Simulations

We used the EMPM to simulate entrainment and mixing in Hawaiian cumulus cloud “main turrets” observed

**Fig. 2.** (a) Variance vs elapsed time scaled by a large-eddy timescale $t_L$ for 1, 3, and 9 initial blobs. (b) As in (a) except that the elapsed time is scaled by the mixing timescale $t_d$, which depends on the initial blob size.

**Fig. 3.** A parcel is represented by a 1D domain in the EMPM. The parcel’s internal structure evolves due to discrete entrainment events and turbulent mixing (rearrangement events and subgrid-scale diffusion).
EMPM Required Inputs

• Required for a classical (instant mixing) parcel model calculation:

  Thermodynamic properties of cloud-base air

  Updraft speed

  Entrainment rate

  Thermodynamic properties of entrained air

  Aerosol properties
• In addition, the EMPM requires:

  Parcel size

  Entrained blob size, $d$

  Turbulence intensity (e.g., dissipation rate, $\epsilon$)
Mixing Time Scale

\[ \tau = \left( \frac{d^2}{\epsilon} \right)^{1/3}, \]

d is blob size, \( \epsilon \) is dissipation rate of turbulence kinetic energy:
\[ \epsilon \sim \frac{U^3}{L} = \frac{u(l)^3}{l} = \frac{u(d)^3}{d}, \]

\( U \) is velocity scale for largest eddies (of size \( L \)); \( u(l) \) is same for size \( l \) eddies. Therefore,
\[ \tau = \left( \frac{d^2}{\epsilon} \right)^{1/3} \sim \left( \frac{d^3}{u(d)^3} \right)^{1/3} = \frac{d}{u(d)}, \]

which is the eddy turnover time for an eddy of size \( d \).

Cumulus cloud: \( U \sim 2 \text{ m/s}, L \sim 1000 \text{ m}, \) so \( \epsilon \sim 10^{-2} \text{ m}^2/\text{s}^3. \)
For \( d = 100 \text{ m}, \) \( \tau \sim 100 \text{ s}. \)
Classic (instant mixing) parcel model is recovered when

- Mixing time scale $\rightarrow 0$

- This occurs when
  
  Entrained blob size $\rightarrow 0$, or
  
  Turbulence intensity $\rightarrow \infty$
Comparison to Measurements

EMPM results can be directly compared to high-rate [1 Hz (100 m) to 1000 Hz (10 cm)] aircraft measurements of temperature, water vapor, liquid water content, and droplet size spectra.
ments. The “instant mixing” profiles are obtained from the EMPM when the entrained blobs are immediately mixed throughout the parcel. For reference, the adiabatic (no entrainment) parcel profiles and the environment profiles are also included in the mean profile plots.

The mean profiles of the conserved quantities $s_l$ and $q_w$ obtained from the EMPM using complete sampling should depend only on the fractional rate of entrainment and not on the entrained blob size (or other aspects of how turbulent mixing is represented). The overlapping gray lines in Fig. 5 confirm this expectation. However, the corresponding mean profiles obtained from the EMPM using conditional sampling do depend on the entrained blob size because the spatial distribution of liquid water (upon which the conditional sampling method is based) is determined by the turbulent mixing process (see section 5d).

By comparing mean profiles from an instant mixing entraining parcel model with the measured (conditionally sampled) profiles, RJB estimated the entrainment rate. This approach ignores the parcel model profiles’ dependence on the entrained blob size. However, the dependence appears to be within the range of measurement uncertainty.

The EMPM standard deviation profiles in Fig. 6 exhibit a significant dependence on the entrained blob size, and also on the sampling method. Only the conditionally sampled $q'_w$ profiles below 850 mb agree better with the measurements than do the completely sampled profiles. The uncertainties in the sampling method and in the measured standard deviation profiles do not allow us to select which entrained blob size is most realistic. However, the comparisons indicate that an entrained blob size in the range 50–200 m provides a good match to RJB’s observations and is certainly more realistic than for any smaller size, as indicated by the instant mixing standard deviations, which are all significantly smaller than the observations. Recall that the instant mixing standard deviations are due solely to the specified variability in cloud base conditions among the realizations.

b. Liquid water mixing ratio and buoyancy

In the previous section we showed that finite-rate mixing is necessary to reproduce the in-cloud variability of the conserved quantities $s_l$ and $q_w$ observed in Hawaiian cumulus clouds by RJB. However, finite-rate mixing is not necessary to match the observed mean profiles of $s_l$ and $q_w$. Are these conclusions valid for nonconserved quantities such as the liquid water mixing ratio, $l$, and the buoyancy?

The buoyancy is proportional to the excess of the virtual temperature in the cloud over the environmental value. For convenience, we define

$$B = T_v - T_w$$

and refer to $B$ as the buoyancy. The appendix describes how $l$ and $B$ are obtained from $s_l$ and $q_w$.

Figure 7 presents the profiles of the in-cloud ensemble means of the liquid water mixing ratio, $\langle l \rangle$, normalized by the adiabatic liquid water mixing ratio, $l_a$, and the buoyancy, $\langle B \rangle$. Figure 8 shows the in-cloud standard deviations of the liquid water mixing ratio, $l'$, and the buoyancy, $B'$. The figures include EMPM in-cloud profiles for entrained blob sizes of 50, 100, and 200 m obtained using both conditional sampling and complete sampling. These figures also include the observed and instant mixing profiles, plus the adiabatic profile for $\langle B \rangle$.

We noted above that the mean profiles of the conserved quantities $s_l$ and $q_w$ obtained from the EMPM using complete sampling do not depend on how turbulent mixing is represented. However, Fig. 7 illustrates that the profiles of $\langle l \rangle/l_a$ and $\langle B \rangle$ obtained from the EMPM using complete sampling do depend on how turbulent mixing is represented because $\langle l \rangle/l_a$ and $\langle B \rangle$ depend on the degree of mixing.

Figure 7 shows that the mean profiles obtained from the EMPM for the three entrained blob sizes using conditional sampling and complete sampling differ in two
the most likely because there is a physical reason for the mixing efficiency to decrease at scales smaller than the smallest eddies.

b. Large-scale picture

Independent of the explanation for the small-scale inhomogeneities sometimes observed, the other observations can be interpreted to make some deductions about large-scale entrainment and mixing.

Because low-concentration regions and occasionally clear air gaps are found well inside a dense cloud, cloud-scale motions must be present and important to the entrainment and mixing process. Note that the region blown up in Fig. 10b is separated from the edge by a higher concentration region. Such observations can only be explained by the effects of large, cloud-scale eddies. A gradient diffusion model of mixing is clearly inadequate.

The fact that regions diluted with environmental air are found well inside clouds but gaps of clear air are rare indicates that the clear air is initially mixed with cloud air before the large-scale motions transport it inwards. Logically this would begin at the cloud edges in regions smaller in scale than the large eddy size, therefore on faster time scales. Since clear air has been occasionally observed inside the clouds, the time scale for initial mixing at the cloud edges, although shorter than that for cloud-scale transport, cannot be very much shorter.

The observations of regions 10–100 m in length that are, within the sensitivity of the Fishing test, homogeneous (at least at scales greater than 10 cm) indicate that regions in that size range have time to homogenize before cloud-scale eddies intermix them or affect them with new entrainment. The time scale for homogenization of such regions cannot be very much shorter than that for cloud-scale eddies or else larger homogeneous regions would be observed.

The observation that the clouds consist of more homogeneous regions than inhomogeneous regions suggests that the large-scale eddy entrainment may be better described as intermittent events than as a continuous process.

The droplet spectra of Fig. 12 have similar shapes and the same mode diameters; only the concentration differs. This phenomenon has been observed and discussed before (Paluch and Knight 1984). If entrainment has caused evaporation of droplets in the low concentration regions, then the spectra are consistent with a mixing process in which some droplets experience total evaporation while others are unaffected. This scenario has been named “inhomogeneous mixing” (Baker and Latham 1979) and occurs when the evaporation time of droplets ($\tau_e$) is considerably smaller than the mixing time scale. The insensitivity of the droplet spectrum modal diameter to dilution, in this case, could be partly due to inhomogeneous mixing and partly due to the insensitivity of the FSSP sizing measurements (Paluch and Baumgardner 1989, section 7). However the modal diameter insensitivity to dilution could also result from the entrained clear air having been already saturated with water vapor.

The time scales in this physical situation are such that no easy visualization can be made. That is, all the relevant time scales are similar in magnitude. A time scale for the largest-scale motions is the characteristic cloud turret size divided by its characteristic velocity, which for the present study is 100–1000 meters divided by several meters per second. Thus, the time scale is on the order of one to several minutes. It has been argued above that mixing between clear and cloud air occurs initially at the cloud edges on time scales shorter but not very much shorter than those for large-scale transport. Likewise, it is argued that the time scale for homogenization of regions 10–100 m in size is shorter but not very much shorter than that for cloud-scale eddies. Finally, cloud droplet evaporation times are also on the order of 1 min. Evidently all the physical processes—initial mixing of clear and cloud air, transport of the mixing regions from the edges to the interior, homogenization of interior regions, and evaporation (with associated latent heat effects) of cloud droplets—occur simultaneously. Figure 13 is an attempt to illustrate the above ideas.

![Fig. 13. Illustration of entrainment and mixing in small cumulus clouds. Key characteristics: initial entrainment and mixing near edges, simultaneous but discrete large-scale entrainment events due to cloud-scale eddies, subsequent homogenization of regions 10–100 m in length.](image-url)
Applying the EMPM to Hawaiian Cumuli

Results

• Based on compositied measurements of active cloud turrets (Raga et al. 1990)

• **Macrophysics:** in-cloud profiles (data: G. Raga)

• **Microphysics:** droplet spectra (data: C. Pontikis)

• **Large-droplet production**
Applying the EMPM to Hawaiian Cumuli

References


Macrophysics: in-cloud profiles
Liquid water mixing ratio normalized by adiabatic value

Liquid water mixing ratio std dev (g/kg)
Microphysics: droplet spectra
no entrainment + finite-rate mixing

entrainment + finite-rate mixing

entrainment + instant mixing

droplet concentration (cm$^{-3}$ µm$^{-1}$)

droplet radius (µm)
finite rate mixing with entrainment
adiabatic
Large-droplet production
finite rate mixing with entrainment
adiabatic

droplet radius (µm)

time (s)

finite rate mixing
with entrainment
adiabatic

time (s)
supersaturation ratio

-0.020 -0.015 -0.010 -0.005 0.000 0.005 0.010 0.015
Some factors that affect large droplet production

- Turbulence intensity (dissipation rate)
- Entrained blob size
- Entrainment rate
- Relative humidity of entrained air
\[ \varepsilon = 10^{-2} \text{ m}^2 \text{s}^{-3} \]

\[ \varepsilon = 10^{-4} \text{ m}^2 \text{s}^{-3} \]

\[ \varepsilon = 10^{-6} \text{ m}^2 \text{s}^{-3} \]
(a) Droplet concentration (cm$^{-3}$) vs. maximum droplet radius ($\mu$m) for different $\lambda$ values: $\lambda=0.5$ km$^{-1}$, $\lambda=1.0$ km$^{-1}$, $\lambda=1.5$ km$^{-1}$.

(b) Droplet concentration (cm$^{-3}$) vs. droplet radius ($\mu$m) for different $\lambda$ values: $\lambda=0.5$ km$^{-1}$, $\lambda=1.0$ km$^{-1}$, $\lambda=1.5$ km$^{-1}$.
Coupling EMPM and 3D large-eddy simulations (LES)

- We will better resolve the SGS structure in 3D LES by implementing a 1D subgrid-scale (SGS) mixing model with a grid size of about 10 cm---a scale of variability that is measurable by aircraft.

- The CPU time required for a LES with a grid size of 0.1 m is $10^8$ more than one with a grid size of 10 m.
Coupling EMPM and 3D LES

CPU times for ODT grid size = 0.1 m with different $(\Delta x)_{LES}$:

<table>
<thead>
<tr>
<th>$(\Delta x)_{LES}$</th>
<th>Relative CPU time</th>
<th>CPU hours</th>
<th>GAUs</th>
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<tr>
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<td>800</td>
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<tr>
<td>5</td>
<td>9</td>
<td>7200</td>
<td>1800</td>
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<tr>
<td>40 (with ODT)</td>
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<td>1600</td>
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<td>7</td>
<td>5600</td>
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Multiscale Modeling Framework

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<th>Stand-alone Averaged</th>
<th>Stand-alone Reduced dimensionality</th>
<th>Coupled MMF</th>
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<tbody>
<tr>
<td>1D Cu par</td>
<td>2D CRM</td>
<td>3D GCM + 2D CRM</td>
</tr>
<tr>
<td>0D parcel model</td>
<td>1D EMPM</td>
<td>3D LES + 1D ODT</td>
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</tbody>
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Conclusions

• Stand-alone and coupled ODT-based models are promising for studying fundamental physics of cloud-turbulence-microphysics-radiation interactions.

• MMF approach is viable for cloud-turbulence scale interactions as well as for synoptic-meso-cloud scale interactions.

• Cross-fertilization of ideas & techniques should be beneficial to further development of both approaches.

• Perhaps coupling GCM, CRM, and ODT will be useful for certain problems, such as aerosol-microphysics-climate interactions...
3.2.2 Project 2: EMPM and LES

In parallel with the EMPM-only studies, we will perform high-resolution LES of BOMEX, ATEX, Hawaiian, SCMS and/or RICO cumulus clouds in order to study the entrainment/detrainment process and to collect trajectories to use to drive the EMPM. We will run and analyze EMPM simulations (with stochastic coalescence and droplet inertial effects) based on a representative set of LES trajectories. This will provide a more realistic range of cloud properties for investigating droplet spectral broadening. By comparing the results using mean or time-varying updraft speeds, entrainment rates, and mixing rates, we can determine the impact of using mean values.

After implementing the linear eddy mixing model as a subgrid-scale mixing model in the LESM, we will perform LEM-LES of RICO cumulus clouds. We will use the results to (1) evaluate this LES approach by comparing the LEM-LES fine-scale structure to RICO measurements, and to (2) evaluate the EMPM’s entrainment and mixing models by comparing the LEM-LES fine-scale structure to corresponding EMPM results.

4 The University of Utah Large-Eddy Simulation Model

The University of Utah Large-Eddy Simulation Model (UU LESM) is specifically designed to examine small-scale atmospheric flows, especially those involving cumulus convection, entrainment, and turbulence. It was developed by Zulauf (2001). The dynamic framework is based upon the 3D nonhydrostatic primitive equations. Rather than using an anelastic set of governing equations, the quasi-compressible approximation is used (Droegemeier and Wilhelmson, 1987), in which the speed of sound is artificially reduced. This allows for a highly flexible code base, while still remaining computationally economical. The prognostic variables include the conserved quantities of liquid water potential temperature and total water mixing ratio. The model uses the Deardorff (1980) subgrid-scale turbulent kinetic energy (SGS TKE) closure, which employs a prognostic equation for SGS TKE. Subgrid fluxes of momentum and scalar quantities are diagnosed using

Figure 5: Vertical (top) and horizontal (bottom) cross-sections of liquid water mixing ratio for BOMEX trade cumulus simulations with resolutions of 40 m (left), 20 m (center), and 10 m (right). The horizontal cross sections are located at $z = 1000$ m. The contour interval is $0.1$ g kg$^{-1}$. The line through each cross-section indicates its intersection with the accompanying perpendicular cross-section. Each cross section displays an area 590 m by 725 m.
Planned EMPM Improvements

• Additional physics:

  Collision and coalescence growth of cloud droplets

  Turbulence effects on droplet clustering

• Better representation of entrainment:

  Use realistic trajectories obtained from a 3D Large-Eddy Simulation Model (LESM).

  Analyze entrainment in the LESM.

  Compare relevant EMPM and aircraft statistics.