Multi-Scale Modeling of Fine-Scale Structure and Droplet Spectral Evolution in Cumulus Clouds

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February 25, 2004
Project Summary

• The 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 propose to investigate are (1) entrainment and mixing, (2) droplet inertial effects, and (3) ultragiant 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 (∼ 1 mm).

- The EMPM can calculate the growth of 1000 individual cloud droplets based on each droplet’s local environment.
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
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 obtained using the ensemble mean cloud base conditions, $l_a$, 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
We propose to extend and improve the physics of the EMPM by adding new physics:

- Stochastic collection growth of cloud droplets
- Droplet inertial effects
and by further evaluating and improving the EMPM S representation of entrainment:

- Using realistic trajectories obtained from a 3D Large-Eddy Simulation Model (LESM),

- Performing detailed analyses of entrainment in the LESM

- Implementing the linear eddy mixing model as a subgrid-scale mixing model in the LESM.
Modeling and Measurements

- In addition to the measurements required to perform a classical (instant mixing) parcel model calculation, the EMPM requires the parcel size, the size (distribution) of the entrained blobs, and the turbulence intensity.

- Initially, we will use the EMPM to explore the effects of entrainment and mixing, droplet inertial effects, and ultragiant nuclei on droplet spectral broadening for realistic ranges of cloud and environment properties.

- To perform and analyze EMPM simulations based on observed cloud and environment properties, we require aircraft measurements of temperature, water vapor, vertical velocity, size-resolved aerosol properties, droplet size spectra, and liquid water content.
We will also perform high-resolution 3D large-eddy simulations (LES) of cumulus clouds in order to:

- evaluate the LES approach by comparing LES fine-scale structure to RICO measurements,

- study the (simulated) entrainment/detrainment process,

- evaluate the EMPM's entrainment parameterization,

- collect realistic trajectories for driving the EMPM.

- We eventually plan to better resolve the SGS structure in a 3D LESM 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.
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 $0.1 \text{ g kg}^{-1}$. 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.
Applying the EMPM to Hawaiian Cumuli

References


Applying the EMPM to Hawaiian Cumuli

Results

- **Macrophysics:** in-cloud profiles (data: G. Raga)
- **Microphysics:** droplet spectra (data: C. Pontikis)
- **Large-droplet production**
Macrophysics: in-cloud profiles
Microphysics: droplet spectra
concentration (cm$^{-3}$ µm$^{-1}$)

droplet radius (µm)
Large-droplet production
no entrainment +
finite-rate mixing

entrainment +
finite-rate mixing

entrainment +
instant mixing
finite rate mixing with entrainment

adiabatic