Influence of Entrainment and Mixing on the Evolution of Cloud and Rain Drops in Cumulus Clouds

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Outline

1. Problems addressed by Baker et al
2. Inhomogeneous and homogeneous mixing
3. The relevance to current problems being tackled with new models

Warner (1969), JAS, **26**, 1049

"It has long been recognized by cloud physicists that there are serious difficulties in accounting fully for the size distribution of the droplets in the early stages of growth before coalescence ... "

"It seems wise, therefore, to describe in some detail the cloud droplet-size spectrum ... in order to see if we can throw some light on mechanisms that may be responsible for broadening the spectrum."

Key problems addressed by Baker et al

- Warner results: Unable to quantitatively explain features of cloud droplet distribution (DSD)

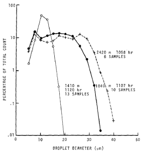


FIG. 2. The average size distribution of all samples taken at three different levels in a cloud based at 1220 m and with tops ~2600 m.

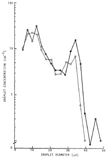


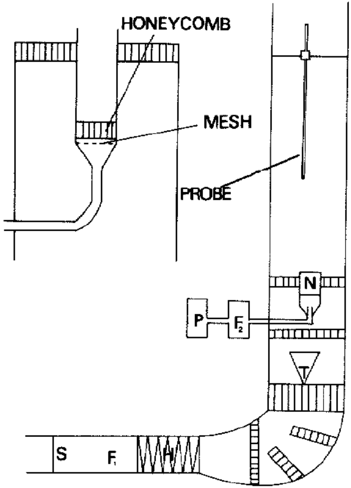
FIG. 1. Adjacent samples taken 100 m apart near the top of a cloud 1400 m deep. Both show a strongly bimodal distribution.

- Warner (1973): Modelling results – simple mixing between cloud and environment is unimportant in determining the DSD
- Mason and Jonas (1974), Jonas and Mason (1974) multi-thermal model: major features of DSD can be explained in terms of mixing between the cloud and its environment
- Long-standing question: measured times to produce raindrops in warm cumulus clouds shorter than modelled values

The concept of inhomogeneous mixing

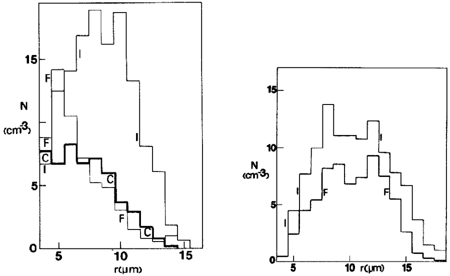
- Mixing is a "non-classical inhomogeneous process in which some droplets – of all sizes – are much more influenced by entrainment than others in their vicinity."
- Nature of mixing depends on relative values of rates of:
  - turbulent diffusion of entrained air, τ_T,
  - evaporation of a droplet, τ_r.

Cloud tunnel used by Latham and Reed, and Baker et al



H – humidifier; T – spinning top; N – nozzle; F_2 – flow-meter; P – pump

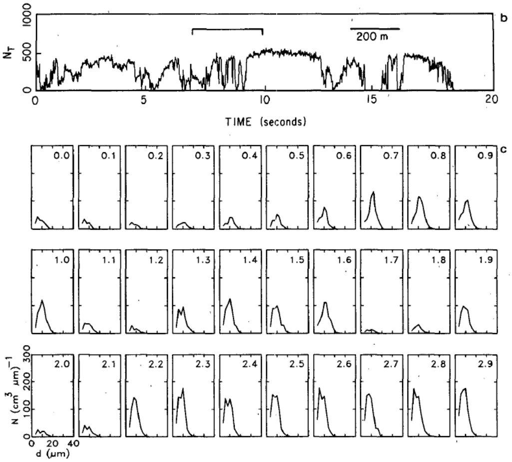
Baker et al. Drop size distributions for small and large nozzles



Small (left) and Large (right) nozzles. Before (I) and after (F) mixing

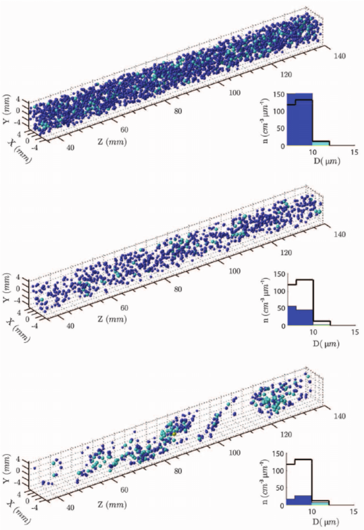
- (Left) If $\tau_T \ll \tau_r$, the inhomogeneities created by entrainment will be smoothed out before significant evaporation can occur.
- (Right) If $\tau_T \gg \tau_r$, the mixing process is slow; extreme inhomogeneous mixing; drops of all sizes completely evaporated in region of mixing, but others, further away unaffected.

Small-scale (10 m) variability away from "core"



Austin et al, JAS, 1985

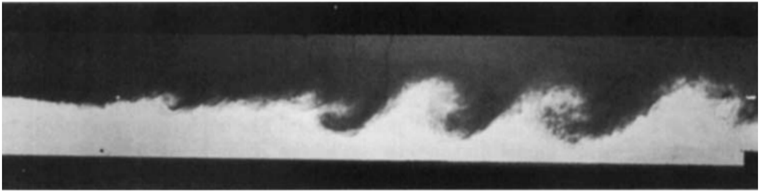
Undiluted; dilute and uniform; and cm-scale variability at edges of clouds



Beals et al, Science, 2 October 2015

Molecular mixing at Kolmogorov scale

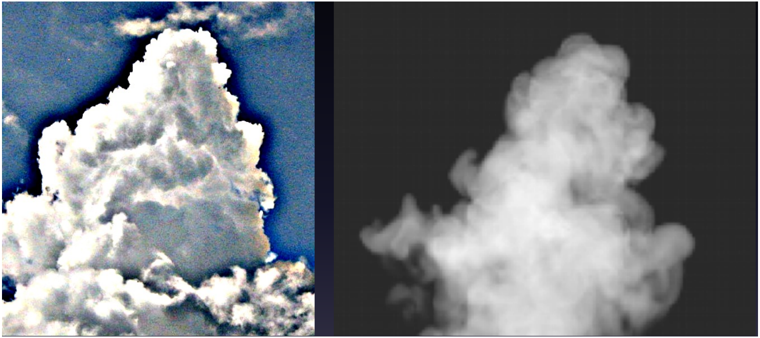
(a)



(b)

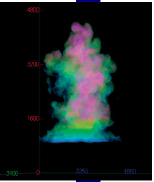
Broadwell and Breidenthal, J. Fluid Mech., 1982

Entrainment and leading edges



Sonia Lasher-Trapp

Calculations of condensational growth along trajectories using parcel model



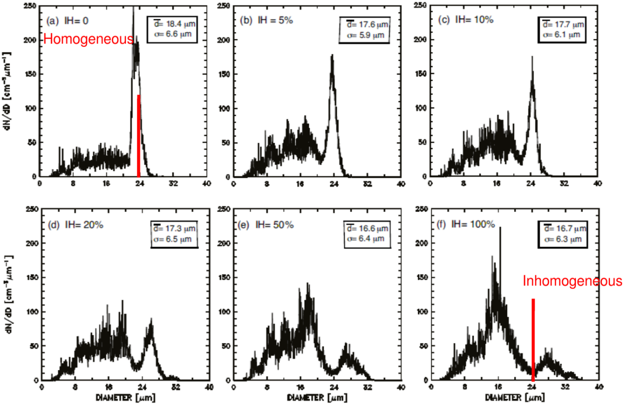
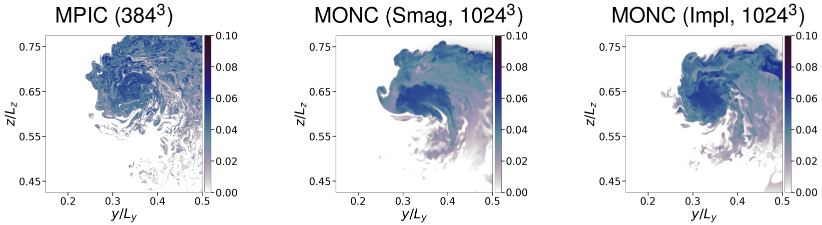


Figure 7. Droplet size (diameter *d*) distributions for the ensemble of parcels reaching target point 1 under increasing degrees of inhomogeneous mixing (IH): (a) 0% (in other words homogeneous mixing), (b) 5%, (c) 10%, (d) 20%, (e) 50%, and (f) 100% inhomogeneous mixing.

Lasher-Trapp et al (2005)

Lagrangian approaches: Moist Parcel-In-Cell (MPIC)

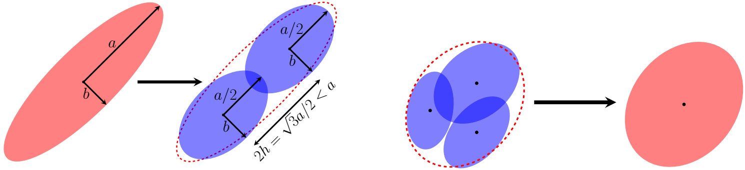
- Numerical diffusion: issue particularly for gridded codes.
- Parcel-based models good for detailed process studies. How to deal with mixing? Let parcels split and merge.
- MPIC: prototype model developed for 3D incompressible flow (Dritschel et al., QJ, 2018; Böing et al., QJ, 2019).
- Spherical parcels carry any number of (conserved) attributes and vorticity (evolved).
- Parcels have a volume V_i in order to determine gridded fields needed to construct velocity $\boldsymbol{u}$ on the grid.



Elliptical Parcel-In-Cell (EPIC)

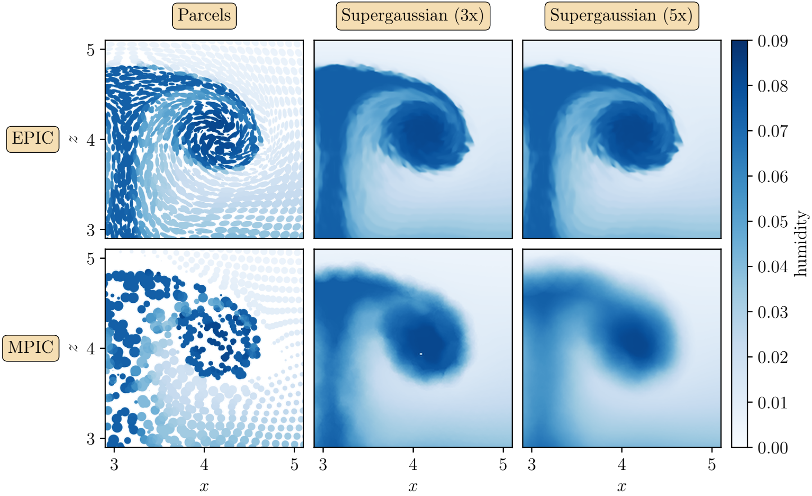
Use deforming ellipses.
Splitting and merging conserve:

- total centroid
- total area
- total second moments (as best as we can)



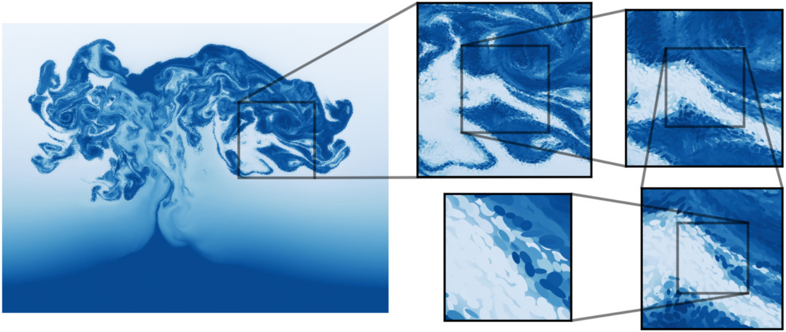
Frey, Dritschel and Böing, JCP-X, 2022 (Grant EP/T025409/1)

Application to 3D clouds

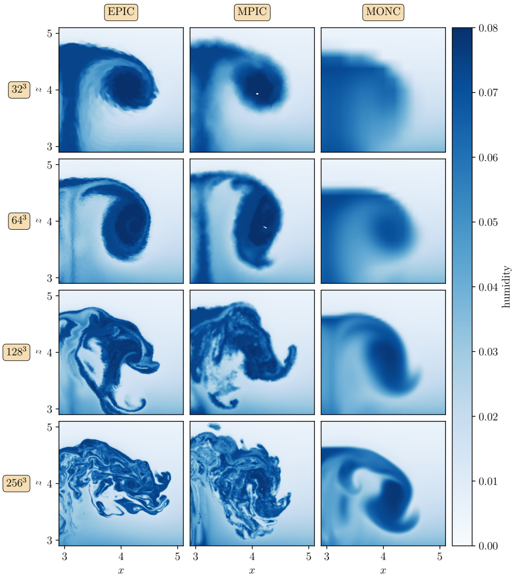


Frey, Dritschel and Böing, under review

Parcel-level behaviour

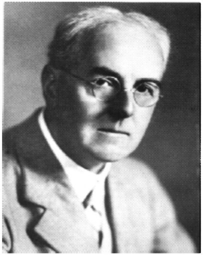


Resolution dependence

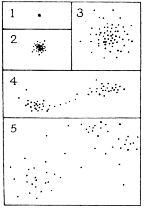


We are missing something still: effect of turbulence at small scales?

- Convergence with resolution is a challenge: at low resolution, too little mixing!
- Additional process: parcels can grow in volume and dilute, inspired by Richardson's and Smagorinsky's work.



These diagrams are, of course, merely illustrative fictions.



FIGS. 1–5.

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Atmospheric Diffusion shown on a Distance-Neighbour Graph.

By LEWIS F. RICHARDSON.

(Communicated by Sir Gilbert Walker, F.R.S.—Received November 7, 1925.)

§ 1. THE NEED FOR A NEW METHOD.

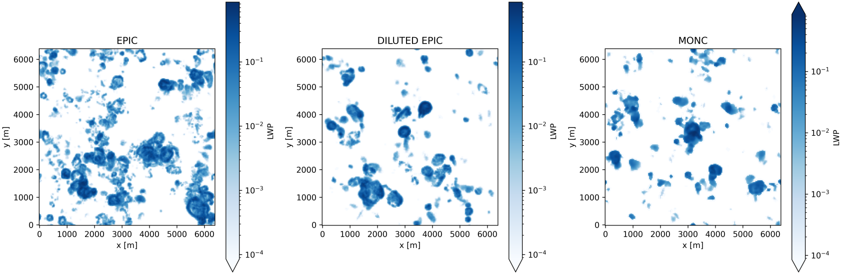
§ 1.1. *Introduction.*

3 c 2

Richardson, Proc. Roy. Soc. A, 1926
Smagorinsky, Mon. Weather Rev., 1963

Work in progress: shallow cumulus case (BOMEX)

- Realistic thermodynamics: potential temperature, liquid water and water vapour.
- Surface fluxes and large-scale processes.
- Small-scale mixing influences cloud patterns in EPIC!



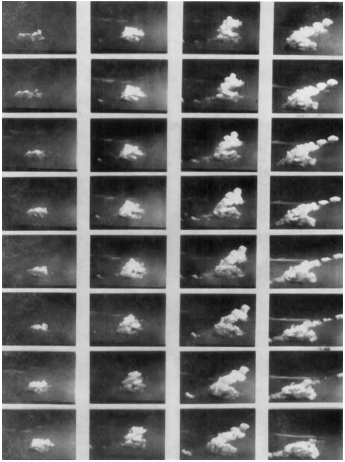
Next steps

- Further work on convergence, small-scale mixing, and its role in cloud organisation.
- Add two-moment droplet scheme: consistent treatment of cloud water content and droplet number. First step to addressing (in)homogeneous mixing.

Visualisation of MPIC simulation: Domantas Dilys. DALL-E 2
Two-moment scheme work is part of CLOUDYTIME (with Thorwald Stein, Alan Blyth, Sue Gray and Chris Holloway) within ParaChute (Alison Stirling and many others).

Next steps

- Shear plays an important role in cumulus dynamics (e.g. Malkus, QJ, 1952).
- EPIC can provide a new prespective on the role of shear in cumulus dynamics, including mixing.



Outlook

- Massively parallel version now exists.
- More flexible boundary conditions, precipitation.
- Application across scales: laboratories, Hadley circulation, chemistry.
- Comparison against flight data, example below is preliminary Wescon FAAM data.