Examination of Entrainment-Mixing Mechanisms Using a Combined Approach

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Motivation

- Entrainment-mixing processes are important but poorly represented in models.

- Entrainment-mixing processes affect Z-LWC relations used in radar retrieval of LWC.

- Entrainment-mixing processes affect evaluation of aerosol indirect effects.

- Entrainment-mixing mechanisms are examined using a combination of microphysics, dynamics and thermodynamics in stratocumulus clouds.
Data

- **Cloud:**
  - Five stratocumulus cases.

- **Time:**
  - The March 2000 cloud Intensive Observation Period (IOP).

- **Site:**
  - Southern Great Plains (SGP), USA.

- **Aircraft:**
  - Citation research aircraft of the University of North Dakota.

- **Instruments:**
  - *Cloud droplet spectra* --- Forward Scattering Spectrometer Probe (FSSP);
  - *Drizzle drop spectra* --- Optical array probe 1D-C;
  - *Particle Image* --- Cloud Particle Imager (CPI);
  - *Air temperature* --- Rosemount Model 102.
Classification of Entrainment-Mixing Mechanisms

- **Homogeneous Entrainment-Mixing**: Just Saturated Air by Droplet Evaporation
  - Entrained Drier Air
  - Unmixed Cloudy Air

- **Inhomogeneous Entrainment-Mixing**: With Subsequent Ascent
  - Entrained Drier Air
  - Unmixed Cloudy Air

- **Extreme Inhomogeneous Entrainment-Mixing**: Just Saturated Air by Droplet Evaporation
  - Entrained Drier Air
  - Unmixed Cloudy Air

Examples:
- Baker and Latham, 1979
- Baker et al., 1980
- Yum, 1998

Diagram showing droplet size and number concentration relationships.
Method One: Microphysics

---Some Examples

**Inhomogeneous mixing with subsequent ascent**
Leg 1 -- 18 March 2000

**Extreme inhomogeneous mixing**
Leg 2 -- 19 March 2000

**Homogeneous mixing**
Leg 2 -- 17 March 2000
Method One: Microphysics

--- Flight Summary

Different colors of Leg numbers:

Blue: extreme inhomogeneous mixing (DOMINANT);
Red: inhomogeneous mixing with subsequent ascent;
Black: homogeneous mixing.

Leg Length > 12 km

03 March 2000
17 March 2000
18 March 2000
19 March 2000
21 March 2000
Method Two: Dynamics

---Damkoehler Number

- **Damkoehler number:**
  
  \[ Da = \frac{\tau_{\text{mix}}}{\tau_{\text{react}}} \]

- **\( \tau_{\text{mix}} \):** the time needed for complete turbulent homogenization of an entrained parcel of size \( L \) (Baker et al., 1984):
  
  \[ \tau_{\text{mix}} \sim (L^2 / \xi)^{1/3} \]

  \( \xi \): dissipation rate

- **\( \tau_{\text{react}} \):** the time needed for droplets to evaporate in a subsaturated blob or a blob to be saturated (Lehmann et al. 2009):

  \[
  \begin{align*}
  \frac{dr_m}{dt} &= A \cdot \frac{s}{r_m} \\
  \frac{ds}{dt} &= -B \cdot s
  \end{align*}
  \]

  \( r_m \): mean radius

  \( s \): supersaturation
Method Two: Dynamics

--- Transition Scale Number (1)

Lehmann et al. (2009) defined transition length ($L^*$) by setting $Da = 1$.

\[
Da = \frac{\tau_{mix}}{\tau_{react}} = 1
\]

\[
\tau_{mix} \sim \left(\frac{L^2}{\xi}\right)^{1/3}
\]

\[
L^* = \frac{\xi^{1/2} \tau_{react}^{3/2}}{\eta}
\]

We define transition scale number ($N_L$) as:

\[
N_L = \frac{L^*}{\eta} = \frac{\xi^{1/2} \tau_{react}^{3/2}}{\eta}
\]

$\eta$: Kolmogorov scale

A larger value of $N_L$ indicates a higher probability of homogeneous process.
Different entrainment-mixing mechanisms tend to occur simultaneously and one dominant mechanism can not rule out the occurrence of the others.

Method Two: Dynamics

---Transition Scale Number(2)
Method Three: Thermodynamics

---Filament Structure

Valid for all legs

Why?

Filament structure is partially responsible for the observed dominance of the extreme inhomogeneous mechanism (Haman et al., 2007).
Microphysics:
- The inhomogeneous entrainment-mixing process occurs much more frequently than the homogeneous counterpart;
- Most cases of the inhomogeneous entrainment-mixing process are close to the extreme scenario.

Dynamics: A new dimensionless number, scale number, is introduced, with a larger value corresponding to a higher degree of homogeneous entrainment-mixing.

Thermodynamics: Sampling average of filament structures also contributes to the dominance of inhomogeneous entrainment-mixing mechanism.
Back up
Filament Structure

Cloud-Free

Sample One

Sample Two

Droplet Concentration

Droplet Size

Extreme inhomogeneous mixing

Leg 2 -- 19 March 2000
Scale-Dependence of Entrainment-Mixing Mechanism

\[ \frac{D_v}{D_{va}} \]

Each Point: every mixing event

\[ \frac{N}{N_a} \]

\[ \frac{D_v}{D_{va}} \]

Burnet and Brenguier (2007)

Each Point: average of 50 successive mixing events
Method One: Microphysics (Summary)

Different colors of Leg numbers:

- Blue: extreme inhomogeneous entrainment-mixing (DOMINANT);
- Red: inhomogeneous entrainment-mixing with subsequent ascent;
- Black: homogeneous entrainment-mixing.
Method Two: Dynamics

---Transition Scale Number(3)
Aircraft Trajectory and Data

Period: March 2000;
Site: Southern Great Plains (SGP);
Instruments: PMS probes (FSSP, 1dc, 2dc, 2dp);
Cloud type: Stratocumulus
The combined microphysical-dynamical-thermodynamic analysis sheds new light on developing parameterization of entrainment-mixing processes and their microphysical and radiative effects in large scale models.