Entrainment and Detrainment in Numerically Simulated Cumulus Clouds and Their Relationship to Buoyancy

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1. Introduction

Entrainment and detrainment in numerically simulated cumulus clouds have been investigated using a cloud-resolving model (CRM) in order to reduce errors induced by cumulus parameterization in coarser-mesh models. Murata and Ueno (2005) investigated the vertical profile of cumulus mass flux using a high-resolution three-dimensional CRM with the 200-m horizontal resolution. They found that the vertical profile of fractional entrainment rate, derived from the calculation based on the vertical gradient of cloud mass flux, have characteristic structures: larger near cloud base and top, and smaller in between (even negative in many cases). The negative values suggest laterally detrained air from a cumulus into the environment. However, it is not clear what factors control the height and amount of detrainment.

In this study, on the basis of the results of the high-resolution CRM simulations, the relationship between detrainment and buoyancy is investigated. We then examine whether buoyancy is useful for determining the height and amount of detrainment in numerically simulated cumulus clouds.

2. Numerical model and experimental design

The numerical model we used was the Japan Meteorological Agency Nonhydrostatic Model (JMANHM; Saito et al., 2006) with the horizontal grid spacing of 200 m (referred to 200 m-NHM). The model was used as a CRM for numerical simulations of cumuli contained in typhoon Songda (2004) just after its genesis. In the numerical simulations, cloud microphysics is explicitly treated and no cumulus parameterization is used. We adopt a grid-nesting strategy for the initial and lateral boundary conditions: quadruple nested JMANHM. Their horizontal grid spacing are 1, 3, 18 km (referred to 1, 3, 18 km-NHM). The initial and lateral boundary data for 18 km-NHM are obtained from forecasts produced by JMA Global Spectral Model (GSM).

3. Detection of entrainment and detrainment

In the analysis of CRM results, assumptions are needed for extracting convective regions from the whole model region. For the extraction, we developed a new method, with which each cumulus area is determined on the basis of convective cores. Some parts of the method followed that proposed by Xu (1995).

For detecting convective cores, the present method uses the horizontal distribution of the maximum cloud updraft strength, Wx, below the melting level, as in the Xu's method. A convective core satisfies one of the following two conditions: 1) Wx > 2Wxa, where Wxa is the average of Wx over the surrounding 24 grid columns, 2) Wx > Wxth, where Wxth = 3.0 ms^{-1}. A cumulus area, in each vertical level, includes a core grid point and other grid points. If the other grid points satisfy the both of the following two conditions, the grid points are assumed to be cumulus grid points. The two conditions are 3) W > Wth, where W is vertical velocity and Wth = 0 ms^{-1}, 4) Qc + Qi > Qth, where Qc and Qi are mixing ratio of cloud water and cloud ice, respectively, and Qth = 0.1 gkg^{-1}.

The entrainment rate calculation was conducted on the basis of the vertical differentiation of updraft velocity as follows: $\partial w / w \partial z$, where w is vertical velocity averaged over a cumulus area and z is height. Positive (negative) values are assumed to represent entrainment (detrainment) in terms of vertical velocity. It should be noted that entrainment rate here is defined on the basis of vertical velocity instead of cloud mass flux because buoyancy does not directly control cloud mass flux but vertical velocity.

4. Relationship between entrainment/detrainment and buoyancy

It is found that favorable heights for detrainment correspond to vertically negative gradient of buoyancy. Figure 1 shows the vertical profiles of vertical velocity and buoyancy in a cumulus area, where buoyancy is defined on the basis of moist air density that includes the effect of water substances. Vertical velocity decreases with height between 5 and 6 km high, indicating that detrainment, in terms of vertical velocity, occurs at those heights. Corresponding to the detrainment, buoyancy decreases with height from 5 to 6 km high.

The correspondence between detrainment and negative buoyancy gradient is observed in many cumulus areas.

The scatter diagram of the relationship between entrainment rate, in terms of vertical velocity, and the vertical gradient of buoyancy is shown in Fig. 2. The diagram for buoyancy instead of the buoyancy gradient is also shown. These figures clearly show the correlation between entrainment rate and the buoyancy gradient rather than buoyancy itself: Positive (negative) buoyancy gradient corresponds to positive (negative) entrainment rate. That is, positive (negative) buoyancy gradient relates to entrainment (detrainment). It should be noted that entrainment rate decreases (i.e., detrainment rate increases) with decreasing the buoyancy gradient. The buoyancy gradient therefore seems to be useful for determining the height and amount of detrainment.

The relationship between the buoyancy gradient and entrainment rate is probably explained by the mechanism proposed by Bretherton and Smolarkiewicz (1989) and Taylor and Baker (1991). They pointed out that the increase of vertical acceleration with height within a cloud brings about a vertical stretch, induces inflow from the environment, and results in enhanced entrainment.

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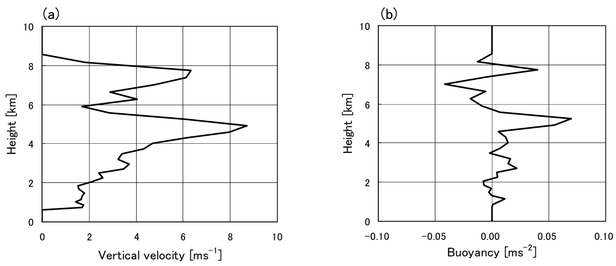

Fig.1 Vertical profiles of (a) vertical velocity and (b) buoyancy, within a cumulus area.

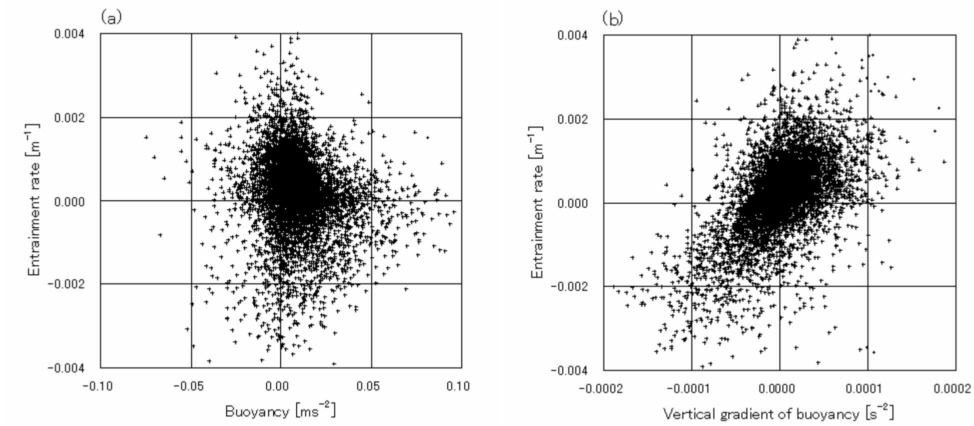

Fig.2 Scatter diagrams of the relationship (a) between buoyancy and entrainment rate, and (b) between the vertical gradient of buoyancy and entrainment rate, within cumulus areas.