EVALUATION OF THE ENTRAINING-DETRAINING PLUME MODEL APPLIED TO THE CUMULUS PARAMETERIZATION OF THE LARGE-SCALE MODEL

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1. INTRODUCTION

Some studies based on observations show that treating cloud as the bulk-entraining plume is questionable (Warner 1970). Telford (1975) presented a vertical mixing model in which the environmental air enters only at cloud top and the air moves to its neutral buoyancy level through vertical mixing and then exits the cloud. Through the measurement of the detrained flux from cumulus, Raymond and Blyth (1986) also showed that the detrainment from the cloud could occur in the horizontally limited area and at every level of the cloud. They also presented a stochastic mixing model in which the mixture of the undiluted cloud air with the ambient air extends up to neutrally buoyant level with only a mixing event and then detrains there. However, it is not clear which kind of physical mechanisms drive the detrainment process. Bretherton and Smolarkiewicz (1989) related the detrainment process to the differential buoyancy of the cloud air with height. Emanuel (1991) developed an episodic mixing model for the cumulus parameterization on the basis of the buoyancy-sorting assumption. Unlike the entraining plume model in which the mixing is continuously and homogeneously occurring, an episodic and inhomogeneous mixing process is considered in this model.

There are several models in which the detrainment below cloud top is considered in the frame of the entraining plume model. Yanai et al. (1973) depicted the information of the bulk properties of the tropical cloud clusters obtained from the large-scale heat and moisture budget using the entraining-detraining plume model. Thus the entrainment and the detrainment were allowed to simultaneously take place at the same height in his model. Tiedtke (1989) developed a comprehensive mass flux scheme for the cumulus parameterization to the large-scale model. He assumed that the entrainment rate was equal to the detrainment rate at any height. This assumption oversimplifies the process of the cumulus cloud causing the height of the cloud top to be decreased. Kain and Fritsch (1990) introduced the cumulus parameterization based on the entraining-detraining plume model for the meso-scale model. They assumed that the two-way exchange of mass between single cloud and its environment was adjusted by the buoyancy-sorting mechanism.

Based on some observational evidences of the detrainment at any height of the cloud (Raymond and Wilkening 1982, 1985; Raymond and Blyth 1986; Raga et al. 1990), the attempt to design the entraining-detraining plume model for application in large-scale cumulus parameterization is examined in this study. This procedure extends the entraining plume model of the modified Arakawa-Schubert scheme (Oh, 1989) in which the moist static energy is used as the indicator of the convective instability instead of the cloud work function in the original Arakawa-Schubert scheme, considering the detrainment at many levels of the cloud, as based on the concept of the buoyancy-sorting mechanism. Thus, the objective of this study is to validate the Entraining-Detraining Plume Model (EDPM) implemented into the modified Arakawa-Schubert scheme using the single column model with the ARM and the GATE data by comparing the observation as well as the results from the Entraining Plume model (EPM). Also, the possibility of the simulation by the EDPM of the different characteristics of the convection events observed in two experiments is examined.

2. DESIGN OF THE MODEL

The entraining-detraining plume model designed for this study is based on the assumption of the spectrum of the cloud ensemble unlike the

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previous approaches (Yanai et al. 1973; Tiedke 1989; Kain-Fritch 1990). In addition, the detrainment of the updraft air is allowed to occur at all levels of the cloud in sub-ensemble cloud as well as at the cloud top, which is based on the concept of the Raymond and Blyth (1986). The property of the detrained updraft air at each level is assumed to have the property of the bulk average of the mixtures of the rising cloud air from the next lower level and the entrained environmental air. Additionally, the larger entrainment rate of the environment air from the lateral side of the cloud means a larger mixing rate with environmental air. It increases the possibility that the mixtures with the neutral buoyancy exist. Consequently, it is a plausible assumption that the detrainment rate of the cloud air is proportionate to the entrainment rate of the ambient air at each level of the sub-ensemble cloud. Finally, in this study, the simple entraining-detraining plume model for the application to the large scale model is developed, in which the cloud ensemble is managed and the properties of the detraining updraft air are assumed as the bulk average of the mixtures at each level.

The cloud mass flux is used to depict the vertical transport of the heat, moisture and momentum by the convection in the family of the Arakawa-Schubert scheme. The cloud mass flux normalized by the cloud-base mass flux is assumed to follow the linear mass flux profile instead of the exponential mass flux which needs too complicated and computationally expensive calculation (Moorthi and Suarez 1992; Ding and Randall 1998). As previously mentioned, the detrainment rate is assumed to be proportional to the entrainment rate with the arbitrary constant (α) below cloud top. On the other hand, the detrainment at cloud top is determined following Arakawa and Schubert [1974]. They assumed that the total detrainment is equal to the total cloud mass flux at the neutral buoyancy level when the detraining layer is shallow.

3. DATA AND EXPERIMENT DESIGN

To validate the cumulus parameterization, the Single-Column Model (SCM) is used with the data of the Atmospheric Radiation Measurement (ARM) program [Stokes and Schwartz, 1994] and the Global Atmospheric Programs Atlantic Tropical Experiment (GATE). The SCM is driven by the large-scale forcing such as the total advective tendencies of temperature and water vapor mixing ratio. For the ARM simulation, the data collected during the 29-day IOP (Intensive Observation Period) that took place from 19 June to 17 July 1997 at the Southern Great Plains (SGP) site as part of the Atmospheric Radiation Measurement project are used. In GATE simulation, the data gathered from the GATE phase III conducted in the summer of 1974 are used. Phase III of GATE covers the period from 00 UTC 30 August to 00 UTC 19 September. In this study, the variables averaged within the area covering from 25°W to 22°W and from 7°N to 10°N are used. The SCM is run during 18 days from 00 UTC 1 September 1974.

Also, the GCM experiments conducted with the Meteorological Research Institute Atmospheric General Circulation Model (METRI AGCM) were carried out in parallel with the SCM experiments.

Figure 1 shows the time-height cross-sections of the observed total advective tendencies of (a) temperature and (b) water vapor mixing ratio for the IOP in the summer of 1997 which are used as a boundary condition in ARM simulation. The right panel depicts the time-averaged profile. The negative tendency of the temperature appears to be concentrated in the higher levels, nearly around 400 hPa, and the relatively small positive tendency showed up below 700 hPa. On the other hand, the positive tendency of the humidity is located in the lower levels (just around 700 hPa), and the negative tendency revealed itself near the surface. This means that the large-scale forcing tends to cool the upper air and moisten the lower air for the iteration period and, as a result, leads the large-scale instability to be consumed by the convection. Particularly, the tendency of the cooling of the upper air and the moistening of the lower air appears to be strong during the 8^{th} day, $11\text{-}12^{th}$ day and 16^{th} day which all roughly correspond to the precipitating periods.

Large scale instability like this leads the stabilizing convective activity and we can see the warming and drying of the environment air resulting from the convection later. The cumulus convection is simulated with observed advective tendencies and then the results are compared with the observation data such as the apparent heat source and the apparent moisture sink as well as the precipitation rate.

4. ARM SIMULATION

Figure 2 shows the time series of the total precipitation of (a) the observation and the simulations by (b) the EPM, (c) the EDPM with α=0.001. The constant, α of 0.001 is determined by the sensitivity tests. The value of r is the correlation coefficients of the simulated result with the observation. In particular, the simulated precipitation rate calculated by the EDPM is more similar to the observation than the EPM. The correlation coefficients of the simulated precipitation rate are calculated by the EPM and the EDPM are 0.21 and 0.53, respectively. The mean precipitation rates of all the simulated ones are about 0.22mm/hr, which is larger that the observed one of 0.18mm/hr. The larger amounts of the simulated precipitation rate may be associated with the more frequent occurrence of the convection by model. The total precipitation rates simulated by two models are largely related to the convective precipitations. That is to say, the similarity of simulated precipitation patterns to observation fields indicates that the convective activity is well simulated by the model. For example, the strong rainfall events (8^{th} day, 11-12^{th} day) occur corresponding to the negative temperature tendency and the positive moisture tendency, i.e., the strong large-scale instability. This pattern of the precipitation is well simulated by the EDPM and also the frequent and weak precipitation which is not shown in the observation data is decreased much more than the EPM over all the iteration period.

The effect of the convection on the environment air is represented by the heating and drying of the environment air due to its compensating subsidence which are associated with the vertical distribution of the cloud mass flux in the cumulus parameterization. Bulk properties of the simulated cloud ensemble related with the cloud mass flux are examined to see if the cumulus parameterization reasonably works for the given large-scale forcing. In addition, the apparent heat source and the apparent moisture sink simulated by the model are compared with the observation data.

5. CONCLUSION

The entraining-detraining plume model is presented for application in the large-scale cumulus parameterization, which considers the detrainment below the cloud top on the basis of the concept of the buoyancy-sorting mechanism [Raymond and Blyth, 1986]. It is assumed that the detrainment rate of the cloud air is much smaller than the entrainment rate, but proportional to the entrainment rate of the environment air and the properties of the detrained cloud air are assumed to be the bulk average of the mixtures at each level.

From the validation of the entraining-detraining plume model using the single-column model with the ARM SGP data and the GATE Phase III data, we found the following results.

- The entrainment mainly occurs below cloud top and the detrainment does at cloud top, while both the entrainment and the detrainment is concentrated at cloud top in case of the entraining plume model. This difference mainly comes from the assumption of the linear mass flux profile instead of the exponential mass flux profile. The large entrainment rate near cloud top leads the occurrence of the convection even under the weak convective instability, which triggers the frequent and weak rainfall in the entraining plume model with the exponential mass flux profile.
- The cloud mass flux which is used to describe the warming and drying by the convection is reasonably simulated corresponding the strong large-scale instability in EDPM.
- The precipitation rate patterns are quite different in both ARM and GATE observation data. The pattern of the GATE precipitation rate over the ocean is smoother than that of the ARM over the land. The entraining-detraining plume model simulates the intensity and the timing of the rainfall as well as this different patterns of two observation data.
- The positive tendency of the apparent heat source in the upper level and the negative tendency of the apparent moisture sink in the lower level are simulated corresponding to the rainfall events, which represent the heating and the drying of the environment by the convection, respectively. The reasonable simulation of these terms means that the influence of the convection on the environment is properly represented by the model.

In the entraining plume model, the apparent heat source and the apparent moisture sink are simulated weaker than the entraining-detraining plume model, which seems to be associated with the smaller cloud mass flux. The smaller apparent heat source and apparent moisture sink seems to cause the frequent and weak rainfall events in the entraining plume model by leading the following convection at the next time step.

No matter how well the single-column model simulates the convective activity, it is difficult to expect the improvement of GCM simulation. That is why the feedback is nonlinear and complicated because the GCM has many uncertainties. Fortunately, the results in the subtropics are slightly improved using the GCM experiment with the entraining- detraining plume model. However, the results in the tropics still need improvement. This improvement includes the followings.

- The warming tendency in the upper-troposphere of the middle latitudes of the Northern Hemisphere, particularly for summer is decreased. This is associated with the weakening of the Hadley circulation which is driven by the diabatic heating of the convection in Tropics. That is why the occurrence of the convection extended to the sub-tropics causes the sinking branch of the Hadley circulation to move northward and leads the warming of the middle-latitude atmosphere through the adiabatic heating by the subsidence as well as the increase of the incidence due to the less cloudiness.

- The globally-averaged annual mean net atmospheric heating is about 5.0W/m2 (4.6W/m2), resulting from the entraining-detraining plume model (entraining plume model). However, the bias of the energy budget decreased in the case of the entraining-detraining plume model, particularly at the top of atmosphere. This is caused by the decrease of the downward short wave radiation and the increase of the upward long-wave radiation at top of atmosphere.

The detrainment below cloud top did not apparently moisturize the environment air as expected in linear sense. Instead of, it changed the simulated bulk properties of the cloud ensemble, which is due to the nonlinear interaction between the cloud ensemble and the environment. Moreover, this change of the simulated bulk properties of the cloud ensemble modifies the inherent triggering mechanism of the simulated convection and leads the reasonable convective activity. However, further study is needed to physically determine the detrainment on the basis of more detailed observations.

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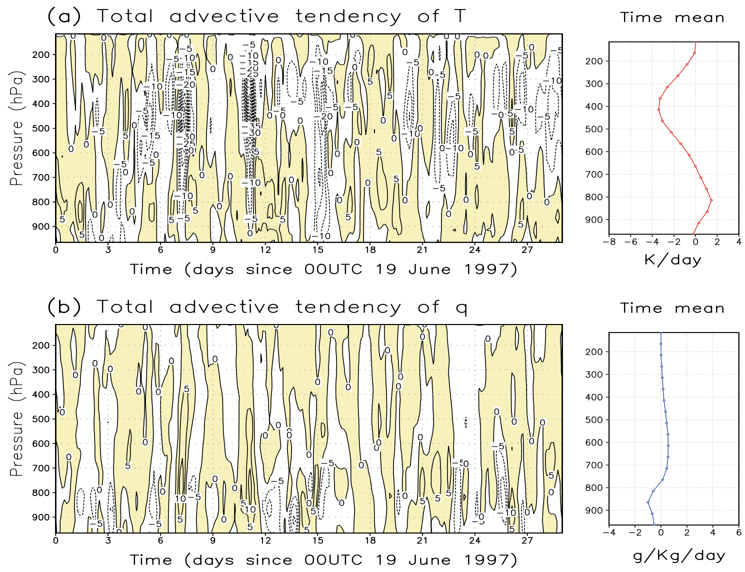

Fig. 1. Time-height cross-section of the observed total advective tendency of (a) temperature and (b) specific humidity for the 29-day of the ARM SGP site starting from 19 June 1997. The contour intervals are (a) 10 K/day and (b) 5 g/kg/day, respectively. The right panel indicates the time mean profile.

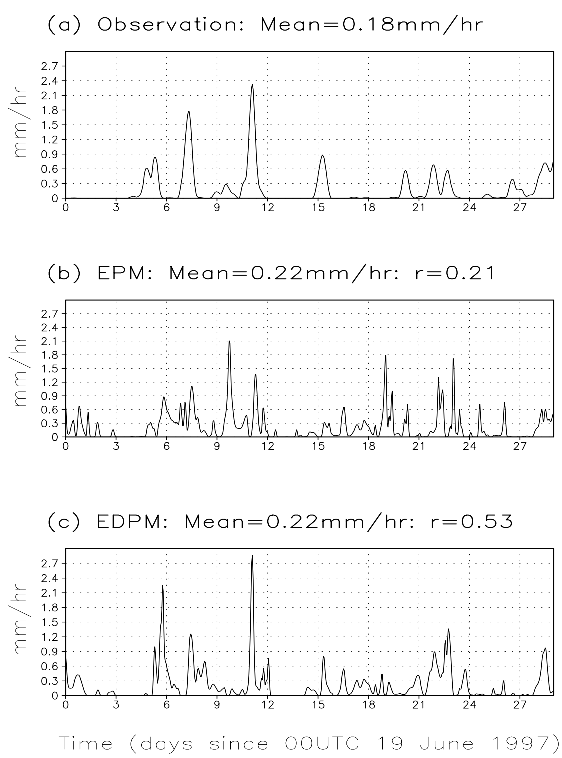

Fig. 2. Time series of the total precipitation (solid) and the large-scale Precipitation (heavy solid) of (a) the observation and the simulations by (b) the EPM with the exponential cloud mass flux, (c) the EDPM with a=0.001 in ARM simulation. r means the correlation of the simulated result with the observation.