NOTES AND CORRESPONDENCE

Importance of Cumulus Parameterization
for Precipitation Simulation over East Asia in June

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Abstract

A regional climate model, NIES/CCSR RAMS, was used with the ECMWF objective analysis data as boundary conditions to reproduce the precipitation pattern over East Asia in June, including that accompanying the Baiu front. In the control experiment, the simulated precipitation pattern was unrealistic, mainly in two respects: precipitation over the Baiu front was too weak, and strong precipitation was found over the North Pacific subtropical high at around 20°N. According to the ECMWF data, strong potential instability is maintained over the subtropical high, under which condition, the cumulus parameterization used in the model predicts strong precipitation to stabilize the atmosphere. Because the lower free atmosphere is very dry over the subtropical high, it is conjectured that the development of deep cumulus convection is suppressed by this dry air in the real atmosphere. When the cumulus parameterization was modified to include this assumption, the intensity of precipitation over the Baiu front as well as the unrealistic precipitation pattern over the subtropical high was clearly ameliorated. The intensification of precipitation over the Baiu front is considered to be due to the increased water vapor transport to the Baiu front, and the decreased stability with respect to the moist convection around the Baiu front. In semi-prognostic experiments with CCSR/NIES AGCM, this modification was found to be also effective in many other parts of the globe. Because problems in precipitation distribution similar to that discussed in the present study are found in many other climate models, the modification of cumulus parameterization suggested here could also be effective in those models.

1. Introduction

Recently, high-resolution climate modeling with horizontal grid spacing of tens of kilometers is becoming available because of the enhancement of computational ability, and the establishment of re-
regional climate modeling techniques (e.g., Giorgi 1995). Precipitation modeling is one of the most difficult issues in climate modeling, because precipitation is a highly complex process related to atmospheric motion, thermodynamics, turbulence, and the microphysics of clouds and other hydrometeors. It is very challenging to compare a precipitation field simulated by high-resolution models with observational data, and to improve the model to make the precipitation simulation as realistic as possible.

An interesting regional pattern of precipitation is that accompanying the so-called Baiu-Meiyu front (hereafter referred to just as the Baiu front), which is a persistent synoptic-scale frontal structure seen over East Asia in early summer. This front is considered to be related to the East Asian summer monsoon, and its formation mechanism has been extensively investigated (e.g., Ninomiya and Akiyama 1992; Kodama 1992; Yoshikane et al. 2001). The study of the precipitation accompanying the Baiu front is important for disaster prevention and water resource management in East Asian countries including Japan, Korea, and China.

It is interesting to note that most of the existing global climate models seem to fail the representation of the precipitation over the Baiu front (Lau et al. 1996). Both ECMWF (Gibson et al. 1997) and NCEP/NCAR (Kalnay et al. 1996) reanalyses also fail to represent the Baiu precipitation (Stendel and Arpe 1998; Fig. 3b). The Baiu precipitation reproduced by global climate models is generally too weak. Some possible reasons for this failure are a lack of model resolution and shortcomings in precipitation schemes. Lau et al. (1998) used a regional climate model with a horizontal resolution of 162 km to simulate the East Asian summer monsoon in June 1994. In their results, precipitation over the Baiu front is considerably weak as well. On the other hand, unrealistically strong precipitation is found over the subtropics (10°–20°N) to the south of Japan, a feature that is also found in the ECMWF reanalysis.

In the present study, a regional climate model with a 50-km horizontal resolution was used to reproduce the precipitation pattern over East Asia in June, including that accompanying the Baiu front. A resolution of 50 km is much higher than that of current generation global climate models (typically hundreds of kilometers) and is considered to be high enough to represent the basic large-scale and synoptic flow patterns related to the Baiu front. In the control experiment, which was conducted without any modifications of the model, precipitation over the Baiu front was found to be too weak. Problems in cumulus parameterization were carefully considered to identify the cause of this failure. A global-scale semi-prognostic test was also conducted to confirm the result.

2. Models and experiments

2.1 Regional climate model and experiment

The regional climate model used in the present study is based on the Regional Atmospheric Modeling System developed at Colorado State University (CSU-RAMS; Pielke et al. 1992), which uses the non-hydrostatic compressible equation. Most of the physics parameterizations of RAMS are replaced by those developed or implemented at the National Institute for Environmental Studies (NIES) and the Center for Climate System Research (CCSR) of the University of Tokyo (hereafter, the model is referred to as NIES/CCSR RAMS). They include a k-distribution 2-stream DOM/Adding radiation scheme (Nakajima et al. 2000), an Arakawa-Schubert-type cumulus convection scheme (Arakawa and Schubert 1974), a prognostic total water scheme for large-scale condensation based on Le Treut and Li (1991), and a land-surface scheme, MATSIRO (Takata and Emori 1999). The implementation of the cumulus convection scheme is based on the prognostic closure proposed by Pan and Randall (1998), in which the cloud base mass flux is treated as a prognostic variable. Simple parameterizations of evaporation of precipitation and downdraft are also included in the cumulus scheme. The vertical diffusion scheme is the level 2.5 closure of Mellor and Yamada (1982), which was originally implemented in RAMS. The computational domain is 4,000 km × 4,000 km in the polar-stereographic horizontal plane with the center at 35°N, 130°E, and is 22.6 km in height. The horizontal grid spacing is 50 km, and the number of vertical levels is 25. The domain includes the Japanese islands, the Korean peninsula, and the eastern part of China (Fig. 1).

The experiments were done for the one-month period of June in an arbitrarily chosen year, 1994 (1 June to 30 June, 1994). The overall intensity of precipitation accompanying the Baiu front of this year was above normal, though precipitation over Japan and Korea was below normal. ECMWF objective analysis data with 2.5° × 2.5° horizontal resolution and twice-daily temporal resolution were
used for the initial and boundary conditions. The modeled wind and pressure fields were nudged to the objective analysis field by the method of Davies (1983) at the 6 outermost lateral boundary grids, while they were also nudged in the interior of the domain with a relaxation timescale of 2 days. The lateral boundary conditions of the temperature and humidity fields were given through strong nudging only at the outermost boundary grids with an inflow wind direction. All the prognostic variables were nudged to the objective analysis data above the tropopause. For the surface boundary conditions, analyzed sea surface temperature (SST) of NCEP (Reynolds and Smith 1994) for June 1994 with $1^\circ \times 1^\circ$ spatial resolution and weekly temporal resolution was used. The data from ISLSCP CD (Meeson et al. 1995) were used to determine the land cover, soil type, and some other land surface characteristics, and to initialize the soil temperature and moisture fields in an off-line fashion as in Dirmeyer et al. (1999).

2.2 Global semi-prognostic experiment

A global climate model, CCSR/NIES AGCM (Numaguti et al. 1997), was used with a horizontal resolution of T42 spectral truncation (which roughly corresponds to 2.8$^\circ$ grid resolution) and 16 vertical levels. This model uses the same physics parameterizations as those in NIES/CCSR RAMS except for a bucket-type land-surface scheme and the level-2 turbulence closure of Mellor and Yamada (1982). The experiments were conducted during the period of June 1994. As a boundary condition, weekly SST data of NCEP (Reynolds and Smith 1994) were used as in the regional experiments. The modeled fields of winds, temperature, and humidity were nudged to the NCEP/NCAR reanalysis data (Kalnay et al. 1996) with a relaxation timescale of 1 day to represent the climate of June 1994 in a quasi-deterministic fashion, and to reduce the model bias. This experiment roughly corresponds to the application of semi-prognostic tests (Lord 1982) to the global scale.

3. Results and discussion

3.1 Control experiment of the regional climate model

Figure 1a shows the observed monthly mean precipitation distribution in June, which is estimated from satellite and gauge observations (CMAP; Xie and Arkin 1996). Because the North Pacific subtropical high-pressure system dominates to the southeast of the Baiu front, little precipitation is
seen there. Figure 1b shows the result of the control experiment (CTL), which was conducted without any modifications of the model. In the CTL, precipitation over the Baiu front is generally weaker than that observed. Especially, the eastern part of the Baiu front is faint. On the other hand, a strong precipitation peak is seen along the southern boundary of the domain, which includes the subtropical high, where the strong precipitation is unrealistic. (Note that the area shown is the whole computational domain.) These features are in agreement with the regional climate model experiment by Lau et al. (1998) and the ECMWF reanalysis. In the present case, most precipitation in the southern part of the domain is convective precipitation (figure not shown). It could be surmised that the unrealistic precipitation along the southern boundary is due to the mismatch of the boundary conditions with the interior model fields. We made a supplementary experiment with the model domain extended by about 1,000 km to the south. It was confirmed that the unrealistic precipitation still appears at almost the same position as in the CTL (figure not shown). Thus, we considered that

the unrealistic precipitation in the CTL is not due to problems in the boundary conditions but, rather, to problems in the cumulus parameterization. A lack of spatial resolution of the model is not likely to be a major cause of the failure either, because 50-km grid spacing should be sufficient to represent synoptic-scale phenomena.

3.2 Observational data analysis

To examine the cause of the unrealistic precipitation in the CTL, relevant atmospheric variables in the ECMWF data were analyzed. Figure 2a shows the monthly mean vertical profiles of moist static energy and saturation moist static energy calculated from ECMWF data. The data averaged over the North Pacific subtropical high, where precipitation is less than 5 mm day$^{-1}$ (the HIGH area depicted in Fig. 1a), are shown by thick lines, while those averaged over the Baiu front, where precipitation is greater than 10 mm day$^{-1}$ (the BAIU area in Fig. 1a), are shown by thin lines. It is clearly seen that the near-surface (0–1 km) moist static energy averaged over the HIGH area is much larger than the saturation moist static energy of the free atmosphere in the same area. This means that a strongly unstable thermodynamic stratification, with respect to moist convection, is maintained over this area. Over the BAIU area, the atmospheric profile is also unstable, but not as strongly as that over the HIGH area.

Figure 2b is the same as Fig. 2a but for relative humidity (RH). As an index of the spatial and temporal variation, the range of one standard deviation is shown as well as the monthly mean because particularly wet conditions due to spatial and temporal variations are considered to be important for precipitation events. Over the HIGH area, the lower free atmosphere (2–4 km) is very dry (the RH is as high as 70% even under relatively wet conditions) due to the subsidence motion accompanying the anticyclone, while it is relatively moist (the RH can be as high as 90%) over the BAIU area. The boundary-layer RH (0–1 km) is, on the other hand, not very different between the HIGH and the BAIU areas.

According to this analysis, it can be concluded that deep cumulus convection is suppressed for some reason over the HIGH area in spite of the strongly unstable profile. One of the most likely reasons for the suppression is the dryness of the lower free atmosphere over the area. Note that, though the areas analyzed here are mostly over the ocean and few radiosonde observations are ex-
pected, the ECMWF data are considered to be fairly realistic there, especially over clear-sky regions (e.g., the HIGH) because they include the TOVS satellite observation retrievals (Eyre et al. 1993). Other possible reasons include a capping inversion at the top of the boundary layer due to subsidence, and a lack of mesoscale updrafts to trigger convections.

3.3 Modified experiment of the regional climate model

To suppress the precipitation over the subtropical high realistically, we tried to introduce some additional conditions to activate cumulus convection. The conditions we have tried include: 1) the vertical wind at the cloud base should be upward and stronger than a critical value; 2) the RH at the cloud base should be higher than a critical value; and, 3) the RH averaged from the cloud base to the cloud top should be higher than a critical value. Since the convection was successfully suppressed only with condition 3, we adopted condition 3. Specifically, if the mean RH of the ambient air of a cloud, \( \bar{RH} \), is smaller than a critical value, \( RH_c \), then the mass flux of the cloud is set to zero. The mean RH, \( \bar{RH} \), is defined by

\[
\bar{RH} = \frac{\int_{z_B}^{z_T} q \, dz}{\int_{z_B}^{z_T} q^* \, dz},
\]

where \( q \) is the specific humidity, \( q^* \) is the saturation specific humidity, and \( z_B \) and \( z_T \) are the heights of the cloud base and top, respectively. Note that, because \( q \) and \( q^* \) rapidly decrease with height, \( \bar{RH} \) mainly reflects the RH of the lower atmosphere above the cloud base though the integration is taken up to the cloud top. The simulated precipitation pattern is sensitive to the value of \( RH_c \); more cumulus convection is activated over the subtropical high with smaller \( RH_c \). In the present study, \( RH_c \) is set to 0.8, which was considered adequate after a series of sensitivity tests.

The physical background of this modification can be found in the work of Gregory and Miller (1989). They concluded from their cloud ensemble model experiments with GATE data that a dry atmosphere above the boundary layer tends to inhibit the formation of deep convection through the entrainment of dry air into the growing cumulus towers. They also pointed out that both Arakawa-Schubert- and Kuo- (1974) type cumulus parameterization fail to represent such process.

Figure 1c shows the result of the experiment with

![Image](image_url)

Fig. 3. The geographical distributions of convectively available potential energy (CAPE) in June 1994 over East Asia: (a) ECMWF analysis data, regional model experiments (b) CTL and (c) RHC.
the modification described above (RHC). In the RHC, the unrealistic precipitation peak along the southern boundary as seen in the CTL is removed, and the intensity of precipitation over the Baiu front, especially its eastern part, is much improved. Although the RHC still presents some problems (for example, precipitation is too weak over surrounding areas of the Baiu front), it represents a clear and qualitative improvement over the CTL.

The relationship between the suppression of precipitation over the subtropical high and the enhancement over the Baiu front is not clear so far. The vertically integrated horizontal water vapor flux constructed from the ECMWF data, and those from the results of the CTL and the RHC are superimposed in Figs. 1a, b and c, respectively. In all the figures, large water vapor flux comes from the South China Sea and from the southern to the western periphery of the subtropical high and flows into the Baiu front. The model results represent the observed water vapor flow fairly well, although the magnitude of the flux is a little underpredicted. In the CTL, the water vapor flux along the periphery of the subtropical high is slightly smaller than in the RHC, but the difference is not significant. It does not seem that the Baiu precipitation is underpredicted in the CTL solely because too much water vapor is removed from the atmosphere at the southern part of the subtropical high, where precipitation is overpredicted and the water vapor flux flowing into the Baiu front is underpredicted.

The convectively available potential energy (CAPE) defined by

\[ \text{CAPE} = \int_{z_p}^{z_T} \frac{g}{T} (T_c - T) \, dz, \]

is shown in Fig. 3, where \( g \) is the gravitational acceleration, \( T \) is the temperature of ambient air, and \( T_c \) is the temperature in the cloud with an assumption of no entrainment. In the ECMWF data (Fig. 3a) and the result of the RHC (Fig. 3c), a large CAPE is maintained in the southern part of the domain, though the CAPE is overpredicted in the middle part of the domain in RHC. On the other hand, in the CTL, the CAPE is very small except around the southern boundary of the domain and over a part of China. (Note that the simulated CAPE at the boundary can be different from that derived from the ECMWF data, since the simulated temperature and humidity were nudged to the ECMWF fields only at the inflow boundary.) This means that, in the CTL, the air flowing into the model domain from the southern boundary becomes stabilized almost immediately due to the unrealistic occurrence of deep cumulus convection. The vertical profile of the air flowing into the Baiu front from the south is too stable in the CTL, which results in the underprediction of the Baiu precipitation in the CTL. On the other hand, in the RHC, because the deep cumulus convection is realistically suppressed over the subtropical high, the vertical profile of the air flowing into the Baiu front is more unstable than in the CTL, which results in the improved intensity of the Baiu precipitation in the RHC over the CTL.

The decrease in the CAPE (i.e., the stabilization)
can generally be interpreted by the combination of three changes: 1) the decrease in boundary-layer humidity; 2) the decrease in boundary-layer temperature; and, 3) the increase in free-atmosphere temperature. In the present case, it is found that the difference in boundary-layer humidity can explain most of the difference in the CAPE between the experiments (figure not shown).

3.4 Global semi-prognostic experiments

To examine the effectiveness of the above-mentioned modification of cumulus parameterization on a global basis, global semi-prognostic experiments were conducted. As in the regional climate model experiments, experiments with and without the modification of cumulus parameterization (RHC and CTL, respectively) were performed. Figure 4 shows the monthly mean precipitation distribution calculated in the experiments, together with the corresponding CMAP data (Xie and Arkin 1996). It is obvious that the simulated precipitation over the Bayu front is stronger and more realistic in the RHC than in the CTL. Precipitation over the North Pacific subtropical high is more strongly suppressed in the RHC than in the CTL. Moreover, the precipitation over the intertropical convergence zone (ITCZ) is also strengthened and improved in the RHC over the CTL. This can be explained in the same manner as in the case of the Bayu front — precipitation over the descending branch of the Hadley circulation is more strongly suppressed in the RHC, and moister and more unstable air flows into the ITCZ. We should note, however, that there is some deterioration of the precipitation pattern in the RHC, such as the weaker precipitation over the Southern hemisphere Indian Ocean.

4. Conclusion

Regional climate model experiments to reproduce the precipitation pattern over East Asia in June were conducted with NIES/CCSR RAMS, and ECMWF objective analysis data as boundary conditions. In the control experiment, the simulated precipitation accompanying the Bayu front was too weak, and unrealistically strong precipitation was found over the North Pacific subtropical high. The analysis of ECMWF data showed that deep cumulus convection is suppressed over the subtropical high in spite of the strongly unstable thermodynamic stratification with respect to moist convection. It is demonstrated that the suppression of deep cumulus convection over the subtropical high should be represented properly to reproduce the precipitation pattern over East Asia in June, including the reasonable intensity of precipitation over the Bayu front. The suppression probably occurs because of the entrainment of dry air into the growing cumulus. The suppression of deep cumulus convection over the subtropical high makes the air flowing into the Bayu front slightly moister, and makes its profile much more unstable than in the case without suppression, which results in a realistic intensity of precipitation over the Bayu front. Many of the existing cumulus parameterizations do not consider such suppression mechanisms. The present study suggests that the lack of cumulus suppression mechanisms is one of the reasons for poor representations of precipitation over the Bayu front in many global and regional climate models. Moreover, it has been suggested that the simulated tropical intraseasonal oscillation is strongly dependent on this kind of cumulus suppression mechanisms; stronger suppression results in larger and more realistic amplitude of the oscillation (e.g., Wang and Schlesinger 1999). Thus, the cumulus suppression mechanisms appear to be important for improving climate simulations both in mean spatial distribution and intertemporal variability.

It should be noted that the modification of cumulus parameterization made here is highly pragmatic. We should further investigate the mechanism of the suppression of deep cumulus convection over the subtropical high through cloud-resolving model experiments and analyses of observational data. A possible better way to represent the suppression mechanism is to account for the buoyancy budget of initial growing cumulus explicitly including the entrainment of ambient air and to explicitly represent the shallow cumulus mixing as a result of the inhibition of deep convection. The improvement of the large-scale condensation scheme is also necessary to represent the overall precipitation pattern well. The interaction between cumulus parameterization and large-scale condensation, including the precipitation from anvil clouds, should also be carefully considered.

The present study also demonstrated that the simulated precipitation patterns are not necessarily improved by simply using a high spatial resolution of the model. With a finer resolution as realized in regional climate models, we can compare a more detailed regional pattern of the simulated precipitation with observational data and possibly find
more detailed problems in our parameterization. We should further look for such specific problems, try to understand the cause of the problems, and improve parameterizations to obtain a better representation of precipitation in regional and global climate models.

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