Improvements in the Subgrid-Scale Representation of Moist Convection in a Cumulus Parameterization Scheme: The Single-Column Test and Its Impact on Seasonal Prediction

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ABSTRACT

This study describes a revised approach for the subgrid-scale convective properties of a moist convection scheme in a global model and evaluates its effects on a simulated model climate. The subgrid-scale convective processes tested in this study comprise three components: 1) the random selection of cloud top, 2) the inclusion of convective momentum transport, and 3) a revised large-scale destabilization effect considering synoptic-scale forcing in the cumulus convection scheme of the National Centers for Environmental Prediction medium-range forecast model. Each component in the scheme has been evaluated within a single-column model (SCM) framework forced by the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment data. The impact of the changes in the scheme on seasonal predictions has been examined for the boreal summers of 1996, 1997, and 1999. In the SCM simulations, an experiment that includes all the modifications reproduces the typical convective heating and drying feature. The simulated surface rainfall is in good agreement with the observed precipitation. Random selection of the cloud top effectively moistens and cools the upper troposphere, and it induces drying and warming below the cloud-top level due to the cloud–radiation feedback. However, the two other components in the revised scheme do not play a significant role in the SCM simulations. On the other hand, the role of each modification component in the scheme is significant in the ensemble seasonal simulations. The random selection process of the cloud top preferentially plays an important role in the adjustment of the thermodynamic profile in a manner similar to that in the SCM framework. The inclusion of convective momentum transport in the scheme weakens the meridional circulation. The revised large-scale destabilization process plays an important role in the modulation of the meridional circulation when this process is combined with other processes; on the other hand, this process does not induce significant changes in large-scale fields by itself. Consequently, the experiment that involves all the modifications shows a significant improvement in the seasonal precipitation, thereby highlighting the importance of nonlinear interaction between the physical processes in the model and the simulated climate.

1. Introduction

Moist convection plays a central role in most of the interactions with physical processes such as dynamical, hydrodynamical, radiative, and surface processes. Therefore, the parameterization of moist convection is

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as discussed in Raymond (1995), the Arakawa–Schubert (1974) scheme (hereafter AS74) is an early example of improving the convective adjustment scheme; however, it requires a high level of sophistication with the assumption of quasi equilibrium. In this regard, the tendency of large-scale motions to produce convective instability is immediately countered by the elimination of this instability by convection; it is assumed that convective instability causes convection. In addition, the AS74 uses a simple cloud model in order to estimate the properties of convection, including the microphysical and precipitation processes of clouds, in terms of resolved conditions. The cloud model of the AS74 considers a budget for mass, static energy, water vapor, and liquid water; additionally, it considers convective precipitation as a fraction of liquid water formed in an updraft.

Previous studies have shown that the representation of the subgrid-scale convective properties in cumulus parameterization scheme significantly influences the model climate in the GCMs (e.g., Cheng and Arakawa 1991; Gregory et al. 1997; Hong 2000; Donner et al. 2001). Cheng and Arakawa (1991) showed that a revised Arakawa–Schubert parameterization including convective-scale downdrafts improves the precipitation pattern associated with the southern Pacific convergence zone (SPCZ) and the Atlantic intertropical convergence zone (ITCZ) due to the enhancement of rainfall over these areas. Gregory et al. (1997) discussed the role of convective momentum transport in the cumulus parameterization scheme and showed that introduction of convective momentum transport reduces a large error in zonal and meridional flow over the Tropics. Hong (2000) suggested that the tuning of parameters such as those for the evaporation of precipitation and downdrafts of clouds improved the climatology of the precipitation pattern over the Tropics. Donner et al. (2001) also showed that the thermodynamic and hydrological aspects of a revised cumulus parameterization scheme that incorporates a convective-scale vertical velocity and mesoscale effects are in agreement with field and observational studies.

The purpose of this study is to evaluate a revised approach for the subgrid-scale convective properties of a moist convection scheme for a simulated model climate. The moist convection scheme utilized in this study is the simplified Arakawa–Schubert (SAS) scheme of the National Centers for Environmental Prediction (NCEP) medium-range forecast (MRF) model (Grell 1993; Pan and Wu 1995; Hong and Pan 1998). The subgrid-scale convective processes of the SAS scheme tested in this study comprise three components: 1) the random selection of cloud top, 2) the inclusion of convective momentum transport, and 3) a revised large-scale destabilization effect considering synoptic-scale forcing. The first two components have been operational at NCEP since 2001, and have exhibited good performance for medium-range forecasts (Global Climate and Weather Modeling Branch 2003); however, they have not been evaluated in terms of seasonal prediction thus far. The last component is newly developed in this study. A single-column model (SCM), which is based on the MRF model, is also devised. Each component in the SAS scheme will be tested within an SCM framework forced by the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) data. The impact of the changes in the scheme on seasonal prediction has been examined for the boreal summers of 1996, 1997, and 1999.

The revised subgrid-scale convective processes in the SAS scheme are described in section 2. In section 3, the SCM utilized in this study is described along with its results. The impact of the revised scheme on the model climate obtained from the ensemble simulation is examined in section 4. The summary and concluding remarks are presented in section 5.

2. Parameterization of subgrid-scale convective processes

The model used in this study is a version of the NCEP MRF model (Kanamitsu et al. 2002a). For precipitation physics, both large-scale condensation and a deep-convection parameterization scheme are employed in this model. A large-scale precipitation algorithm checks for supersaturation of the predicted specific humidity. If supersaturation is found, latent heat is released to adjust the specific humidity and temperature to saturation.

The cumulus parameterization for deep convection employs the SAS scheme in the MRF model. It follows the results of Pan and Wu (1995), which, in turn, is based on the AS74—as simplified by Grell (1993)—with a saturated downdraft. A turbulence-based trigger function proposed by Hong and Pan (1998) is also employed in the SAS scheme. In this section, two modification components in the SAS scheme, namely, the random selection process of the cloud top and the inclusion of convective momentum transport, are explained briefly. The revised large-scale destabilization effect considering the synoptic-scale forcing developed in this study is described in detail. The scheme without the three modifications is referred to as the control SAS scheme, while that which includes these modifications is referred to as the revised scheme.
a. Random selection of cloud top

The control SAS scheme allows for only the deepest cloud. The cloud model in this scheme is based on an entraining plume model: air rises through the cloud-base level and mixes with laterally entrained environmental air as it moves upward. The detrainment of the updraft is arbitrarily allowed only at the cloud-top level. Moreover, the cloud model incorporates a downdraft mechanism and the evaporation of rainfall. The entrainment of updraft and the detrainment of downdraft in the subcloud layers are included. In the control SAS scheme, the cloud-top level is determined as the equilibrium level, while the downdraft-originating level is fixed at a level at which the environmental moist static energy is minimum.

However, this simplification for treating the cloud ensembles also results in some drawbacks. Emanuel and Zivkovic-Rothman (1999) pointed out that the SAS scheme exhibits an extremely dry condition above the 600-hPa level in contrast to a wet condition near the 150-hPa level in the single-column test using the Global Atmospheric Research Programme (GARP) Atlantic Tropical Experiment (GATE) data. It is also reported that the SAS scheme with a prognostic cloud water scheme makes the cloud-top detrainment extremely concentrated in the upper atmosphere (Global Climate and Weather Modeling Branch 2003). The selection process of the cloud top is modified in order to overcome the drawback of determining a very high cloud-top level by considering the deepest cloud.

Because of these reasons, in the revised SAS scheme, the actual cloud-top level is randomly determined between the highest top level and the downdraft-originating level. The highest cloud top in the revised scheme is the cloud top in the control SAS scheme that is determined as the first neutral level upward from the cloud base. The downdraft-originating level is the level of minimum equivalent potential temperature. The random selection of the cloud top is readily performed by multiplying a random number from 0 to 1 by the highest cloud-top level. In addition, after the cloud-top level is determined by a random selection process, the appropriate entrainment rate is recalculated in order that the air parcel becomes neutral at the new cloud top. This selection algorithm is similar to the study of Frank and Cohen (1987). In the study of Frank and Cohen (1987), the cloud size of a single cloud in each grid box is controlled by the entrainment rate inversely proportional to the updraft mass flux, and they found that the taller, dominant clouds in the parameterization scheme act to dry the atmosphere at most levels. Kain (2004) also discussed ways of allowing the more physically based entrainment rate to vary as a function of large-scale forcing. Consequently, the cloud-top selection process is expected to relax the limitation of one extremely mature cloud due to producing a spectrum of clouds of different sizes within the domain, even though the modified approach in this study still has only one cloud.

b. Convective momentum transport

As the second component of the revised SAS scheme, the parameterization of the convective momentum transport is also included. According to Han and Pan (2006), spurious hurricane development in the high-resolution global and regional forecast model was successfully suppressed by the inclusion of the convective momentum transport. However, they found that the convective momentum transport parameterization only including the momentum exchange terms makes the hurricane intensity much weaker, when compared to the observations, due to too much vertical mixing in the environmental flow. A parameterization of the convective-induced pressure gradient force in the convective momentum transport was introduced in their study, and therefore this parameterization method helped forecast hurricane intensity close to the observations.

Based on the study of Han and Pan (2006), the convective momentum parameterization consists of formulations for the subsidence of environmental air that compensates the cloud mass flux, detrainment of momentum from clouds, and convective-scale horizontal pressure gradient force by the following:

$$\frac{\partial \mathbf{V}}{\partial t} = \frac{1}{\rho} \frac{\partial \mathbf{V}}{\partial z} + \delta(\mathbf{V}_u - \mathbf{V}) + \frac{1}{\rho} \mathbf{V}_p \mathbf{u}_v.$$

(1)

Here, $\mathbf{V}$ represents the domain-averaged wind vector, $\mathbf{V}_u$ is the mean-horizontal wind vector of the updrafts, $\mathbf{V}_p$ is the updrafts’ mass flux, $\delta$ is the mass detrainment at the cloud boundaries, $\mathbf{u}_v$ is the fractional area of the updrafts, and $\rho$ is the pressure perturbation. According to Wu and Yanai (1994), the convective-induced pressure gradient force term (the last term in right-hand side) in Eq. (1) can be parameterized using the updrafts mass flux and vertical wind shear and then Eq. (1) can be replaced by

$$\frac{\partial \mathbf{V}}{\partial t} = (1 - \gamma)M_u \frac{1}{\rho} \frac{\partial \mathbf{V}}{\partial z} + \delta(\mathbf{V}_u - \mathbf{V}).$$

(2)

Here, the $\gamma$ is a proportionality parameter and is set to be 0.55 according to Zhang and Wu (2003).

c. Large-scale destabilization effect

The control SAS scheme (Pan and Wu 1995) adopts the quasi-equilibrium assumption in the AS74 as the closure assumption as follows:
\[
\left( \frac{dA}{dt} \right)_{LS} + \left( \frac{dA}{dt} \right)_{CU} \approx 0.
\]  (3)

Here, the subscripts LS and CU denote the large-scale and cumulus contributions, respectively. The \( A \) is a cloud work function (CWF), which is a measure of the buoyancy of the cloud, similar to the convective available potential energy [see Pan and Wu (1995) and Grell (1993) for more details]. This closure assumption assumes the form of a balance between the generation of moist convective instability by large-scale processes and its elimination by clouds. An estimate of the large-scale destabilization in Eq. (3) is provided by the time rate of change of the CWF during an adjustment time scale \( \Delta t \) as follows:

\[
\left( \frac{dA}{dt} \right)_{LS} = \frac{A' - A_0}{\Delta t}.
\]  (4a)

Here, the \( A' \) is the CWF calculated from the environment and \( A_0 \) is a climate CWF. According to Lord and Arakawa (1980), when both large-scale and cloud processes are operating, CWF values calculated from a variety of datasets in the Tropics and subtropics fall into a well-defined narrow range. It follows that the observed time mean CWF values can be used as \( A_0 \) in a large-scale prognostic model, and the climate CWF \( A_0 \) is provided by Lord et al. (1982).

However, the estimated large-scale destabilization of Eq. (4a) is used as a modified form in the control SAS scheme of the MRF model as follows:

\[
\left( \frac{dA}{dt} \right)_{LS} = \frac{A' - c_2 A_0}{c_1 \Delta t}.
\]  (4b)

The tunable parameters \( c_1 \) and \( c_2 \) in the control SAS scheme are empirically determined for the short- and medium-range forecasts as a function of the environmental vertical motion at the cloud base (see appendix A). However, employing the cloud-base vertical velocity can cause some difficulties. One difficulty is that vertical velocity is highly dependent on the grid size of the model. This means that the function for the tuning of the climate CWF can be changed whenever the model is selected with a different spatial resolution. Another difficulty is that the correction of the climate CWF due to the vertical velocity occurs pointwise in the control SAS scheme. Therefore, a more physically robust method for determining the destabilization of clouds for a climate CWF is suggested:

\[
\left( \frac{dA}{dt} \right)_{LS} = \frac{A' - f(x) A_0}{\Delta t}.
\]  (5)

In Eq. (5), we assume that \( A_0 \) is modified by a large-scale contribution function \( f(x) \). This implies that the large-scale destabilization should be specified as the rate at which the given instability of an air column will be neutralized, and it should be different based on the large-scale forcing of the environment, as discussed by Pan and Wu (1995). Thus, we define the function \( f(x) \) as

\[
f(x) = \frac{1}{\pi} \left[ \frac{\pi}{2} - \tan^{-1}\left( \frac{x}{a} \right) \right].
\]  (6)

Here, \( x \) represents the large-scale moisture convergence that is spatially averaged over a certain effective space. The tunable parameters in Eq. (6) are explained in detail in appendix B. Consequently, this approach has the major advantage of resolution independence, and it also considers synoptically organized dynamic forcing for explicit modulation of the cloud properties.

3. Single-column experiments

a. Single-column model (SCM) and experimental designs

The SCM in this study is developed to test the impact of each modification described in section 2 because it is widely known that an SCM is an economical framework for developing and diagnosing the physical processes in climate models, although it lacks the more complete dynamical feedback mechanism (Randall et al. 1996). The physics packages in the SCM are the same as those in the 3D MRF model. The prognostic, single-column test involves the integration of the following conservation equations for the temperature and water vapor mixing ratio:

\[
\frac{\partial T}{\partial t} + (\mathbf{V}_H \cdot \nabla) T + \left( \mathbf{\omega} \frac{\partial T}{\partial p} \right) = \left( \mathbf{\omega} \frac{\alpha}{c_p} \right) + P_T,
\]  (7a)

\[
\frac{\partial q}{\partial t} + (\mathbf{V}_H \cdot \nabla) q + \left( \mathbf{\omega} \frac{\partial q}{\partial p} \right) = P_q,
\]  (7b)

where \( \mathbf{V}_H \) is the horizontal velocity, \( \mathbf{\omega} \) is the vertical velocity, \( \alpha \) is the specific volume, and \( c_p \) is the heat capacity at constant pressure. Here, \( P_T \) and \( P_q \) represent the “physics” that affect \( T \) and \( q \), respectively. In Eqs. (7a) and (7b), the terms enclosed in square brackets are those that are obtained from the observations. For the horizontal and vertical wind components, we simply apply an interpolation between two observations with an observational time interval.

To provide observational forcing to the SCM, we use the data of an intensive flux array (IFA) that is operated from 0000 UTC 20 December to 0000 UTC 26 December 1992 in the western equatorial Pacific as part of TOGA COARE (e.g., Ciesielski et al. 2003). This case has been described by Krueger (1997), which is the
second intercomparison case of the Global Energy and Water Cycle Experiment (GEWEX) Cloud System Study (GCSS) working group 4. Several convective episodes occurred during this 6-day period with varying degrees of rainfall intensity. During this period, the convection was not as well-organized as the strong squall line; however, the systems had a substantial mesoscale component.

In this study, the SCM is operated in a relaxation mode (Randall and Cripe 1999), where the temperature and moisture profiles are relaxed to the observed profiles using a time constant of 24 h, as considered by McFarquhar et al. (2003). The time integration is performed at 10-min intervals from 0000 UTC 20 December 1992. The outputs are obtained at 1-h intervals.

To evaluate the revised SAS scheme, we performed five experiments, as shown in Table 1. The CNTL experiment is a test conducted with the control SAS scheme, while STCP, CMTP, and LSDP are those that utilize the revised SAS scheme for the individual modifications. SALL refers to the experiment based on the revised SAS scheme with all the modifications.

b. Results and discussion

In general, the temporal evolutions of the surface rainfall are in good agreement with the CNTL and SALL experiments and the TOGA COARE data (Fig. 1). The correlation coefficients for all the experiments are approximately 0.8 (Table 2). The first three peaks on 1200 UTC 20, 21, and 22 December 1992, and the last peak on 1800 UTC 24 December 1992 are reproduced satisfactorily. However, both the experiments underestimate the amount of rainfall in general. It is also observed that the timing of the simulated rainfall is delayed by less than 6 h, similarly to other SCM researches (cf. Guichard et al. 2004). Furthermore, less convection during the first 12 h and an intermediate period on 23 December 1992 are apparent. Moreover, the contributions of each component due to the param-
amount, whereas the other experiments show a decrease in large-scale rainfall and an increase in convective rainfall. The reason for this partitioning in the SCM framework cannot be clarified in a straightforward manner. This issue will be elaborately discussed in the 3D tests described in the next section.

The small change in total precipitation among the experiments in the SCM framework is connected with the small change in the mean temperature and moisture fields. In Figs. 2a,b, the CNTL experiment shows a cold and moist bias in almost the entire convective layer as compared with the TOGA COARE observation. The SALL experiment produces a profile similar to that of the CNTL case. However, the difference between the two experiments is most evident in the lower atmosphere below the 850-hPa level and in the upper troposphere between the 400- and 200-hPa levels. Figures 2c,d show the differences in each modification from the CNTL case. These two figures highlight two important features. One is that the change of the SALL case in the temperature and moisture fields is more distinct than that due to any of three components and also that it is different from the linear sum of the change due to each component. This implies that the combined effect of the three modifications in the SALL case is probably not manifested as a linear combination. The second is that the random selection of the cloud top is the main contributor to the change in the moisture and temperature profiles in the SALL experiment, particularly in the upper troposphere. In fact, in the STCP and SALL experiments, a change in the detrainment level due to lowering a cloud top by the random selection processes results in more humid profiles, and cooling corresponding to the moistening occurs in the upper level. On the other hand, warming effects in the SALL case appear in the upper layer from 400 to 300 hPa and in the lower level below 800 hPa. Additionally, drying effects related to the warming in the SALL run appear in these layers.

The change in the temperature and moisture fields in the STCP and SALL experiments is primarily induced by the change in the convective heating profiles. This is clearly shown by the differences in the profiles of the apparent heat source and moisture sink calculated from the SALL and CNTL experiments in Fig. 3. Figure 3 represents the temporal difference between the SALL and CNTL experiments during the heavy rain period from 1800 UTC 23 December to 0600 UTC 25 December 1992, when the SALL case simulates more convective rainfall and exhibits large differences in the temperature and moisture profiles. During this active convection period, the SALL case in Figs. 3a,b shows large cooling and moistening effect in the upper layer from the 300- to 200-hPa level in the beginning of rainfall. Also, warming effects appear in the layer below 300 hPa. Meanwhile, Figs. 3c,d represent the apparent heat source and moisture sink, respectively, and are obtained from the equations of Yanai et al. (1973). From the difference in the convective heating profile, it is evident that the SALL experiment produces more heating and drying at the 400-hPa level and below, whereas it produces cooling and moistening near the 300-hPa level. The change in the convective heating profile is mainly induced by the lower cloud tops due to the random determination of the cloud tops.

In the SCM framework, the parameterized convective processes in the CMTP and LSDP runs show a profile similar to that of the CNTL case. However, as noted in section 3a, the large-scale wind field is simply obtained from the observations during the SCM simulation; although the effect of dynamical feedback is very important in these two experiments, these two processes are based on the parameterization of the convective properties closely related to the large-scale dynamical processes. Therefore, the effects of the convective momentum transport and large-scale destabilization will be better examined within the three-dimensional model framework in the following section.

### 4. Impact on seasonal prediction

#### a. Model and experiment setup

Against the SCM approach, the impact of the revised parameterization on seasonal prediction using a 3D global model framework is investigated. We performed five additional experiments similar to those in the single-column tests. The MRF model utilized in the seasonal simulation employs a resolution of T62L28 (triangular truncation at wavenumber 62 in the horizontal

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### Table 2. Mean rainfall amount (mm day \(^{-1}\)) obtained from each experiment in the SCM framework and TOGA COARE data during 0000 UTC 20 Dec–0000 UTC 26 Dec 1992. The values in the parentheses indicate the temporal correlation coefficients over the TOGA COARE and simulated precipitation.

<table>
<thead>
<tr>
<th>Expt</th>
<th>Total rain (A)</th>
<th>Convective rain (B)</th>
<th>Ratio (\frac{(A - B)/B; %}{(A - B)/B; %})</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOGA COARE</td>
<td>23.9</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>CNTL</td>
<td>19.1 (0.80)</td>
<td>17.9</td>
<td>6.9</td>
</tr>
<tr>
<td>STCP</td>
<td>19.0 (0.81)</td>
<td>17.9</td>
<td>6.6</td>
</tr>
<tr>
<td>CMTP</td>
<td>19.6 (0.84)</td>
<td>18.5</td>
<td>5.6</td>
</tr>
<tr>
<td>LSDP</td>
<td>19.3 (0.83)</td>
<td>18.5</td>
<td>4.5</td>
</tr>
<tr>
<td>SALL</td>
<td>19.5 (0.82)</td>
<td>18.8</td>
<td>3.6</td>
</tr>
</tbody>
</table>

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and 28 terrain-following sigma layers in the vertical). The five-member ensemble runs for each experiment were performed with an approximate four-week lead time for the boreal summers (June–August) of 1996, 1997, and 1999. These three years were selected to examine the response of the convective parameterization scheme to different sea surface temperature (SST) anomalies as a surface boundary forcing. The initial data for each ensemble were obtained from the NCEP reanalysis-II data (Kanamitsu et al. 2002b), ranging from 0000 UTC 1 May to 0000 UTC 5 May with a 24-h interval. As the surface boundary condition, the observed SST data were used with a resolution of $1^\circ$ (Reynolds and Smith 1994) during the simulation period. For the evaluations, the observed precipitation was obtained from the Climate Prediction Center (CPC) Merged Analysis Monthly Precipitation (CMAP) data (Xie and Arkin 1997), and the observed large-scale fields were obtained from the NCEP reanalysis-II data (Kanamitsu et al. 2002b).
b. Results and discussion

1) Precipitation

First, global mean values of simulated precipitation and their pattern correlation coefficient with the observation are examined in Table 3 to investigate the impact of the revised parameterization method on the global precipitation pattern for each year. In this table, the pattern correlation coefficient of two spatial fields is formally calculated the same way as the sample correlation coefficient of a pair of time series, except for using the grid values of two fields and their spatial mean. In general, it is apparent that the SALL experiment results in an improvement in the global precipitation distribution. In comparison with the observation, the CNTL run yields approximately 30% more precipitation and a coefficient of 0.64–0.67 for the three years. As compared with the CNTL case, the SALL experiment shows a decrease in the amount of global rainfall by approximately 10%; however, the latter has an improved precipitation pattern, showing a correlation coefficient of 0.71–0.76. In this table, it is obvious that the STCP and LSDP cases maintain a precipitation pattern similar to that of the observations, while the CMTP case does not. To investigate the mean difference in precipitation due to the individual modifications, we considered the mean precipitation during summer averaged for 3 yr (1996, 1997, and 1999) in Figs. 4 and 5. All the figures in this section show 3-yr means because the significant change that occurs in the atmospheric structure due to each modification in the revised parameterization method is considerably similar in each year, except for the changes in the location

![Image](http://journals.ametsoc.org/mwr/article-pdf/135/6/2135/4233704/mwr3397_1.pdf)

**Fig. 3.** Temporal evolution for the difference between the SALL and CNTL runs in the SCM framework. Differences in (a) $T$ (K), (b) RH (%), (c) apparent heat source (K day$^{-1}$), and (d) moisture sink (K day$^{-1}$) obtained from cumulus convection. Each temporal evolution is averaged with 3-h moving window. Shaded areas denote negative values, and zero lines are omitted.

<table>
<thead>
<tr>
<th>Expt</th>
<th>1996</th>
<th>1997</th>
<th>1999</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMAP</td>
<td>2.71</td>
<td>2.73</td>
<td>2.55</td>
</tr>
<tr>
<td>CNTL</td>
<td>3.55 (0.67)</td>
<td>3.62 (0.64)</td>
<td>3.57 (0.66)</td>
</tr>
<tr>
<td>STCP</td>
<td>3.46 (0.75)</td>
<td>3.49 (0.70)</td>
<td>3.48 (0.52)</td>
</tr>
<tr>
<td>CMTP</td>
<td>3.41 (0.64)</td>
<td>3.45 (0.57)</td>
<td>3.45 (0.48)</td>
</tr>
<tr>
<td>LSDP</td>
<td>3.50 (0.70)</td>
<td>3.58 (0.65)</td>
<td>3.52 (0.69)</td>
</tr>
<tr>
<td>SALL</td>
<td>3.35 (0.76)</td>
<td>3.38 (0.73)</td>
<td>3.36 (0.71)</td>
</tr>
</tbody>
</table>

**Table 3.** Global mean precipitation (mm day$^{-1}$) obtained from each experiment and CMAP data during the summertime for 3 yr, respectively. The values in parentheses indicate the pattern correlation coefficient between the CMAP data and the simulated results for global precipitation.
or intensity of the response of the revised convective parameterization scheme due to the difference in SST forcing. In comparison with the observation, the CNTL case satisfactorily reproduces the tropical rainfall (Figs. 4a,b). The CNTL run represents a strong precipitation zone over the equatorial eastern Pacific and Atlantic Oceans, and it shows a good correlation coefficient of 0.68 in a 3-yr mean. However, the CNTL experiment has some discernible defects: excessive rainfall in the trade wind region north of the equator and underestimated precipitation over the equatorial western Pacific near the Maritime Continent (Fig. 4c). Consequently,
the CNTL run shows twice as many ITCZ rainfall bands over the western Pacific.

The other experiments also reproduce the global pattern similar to the observational precipitation (Fig. 5). However, they exhibit distinct features for each modification. From Fig. 5, it is obvious that the improvement in the overall precipitation pattern is considerably more pronounced in the SALL experiment than in the experiments with individual modifications. Additionally, it is noticeable that the variability of the simulated precipitation is considerably larger in the STCP and CMTP cases than in the LSDP run. The STCP case shows an improvement in the overall rainfall pattern toward the observed precipitation (Figs. 5a,e). This case includes a reduction in the excessive rainfall along the trade wind region north of the equator and more organized rainfall over the western ITCZ. In the CMTP case (Figs. 5b,f), an overall decrease in rainfall occurs over the western Pacific, but not over the eastern Pacific. An excessive decrease in rainfall over the western Pacific in the CMTP case induces a poorer pattern than that of the observation. The LSDP run (Figs. 5c,g) produces a pattern similar to that of the CNTL case over the entire Pacific area, whereas it results in increased rainfall over the south Asian region as compared with that of the control case.

In the SALL experiment, which includes all the three modifications described in section 2, the precipitation pattern is in good agreement with that of the observation (Figs. 5d,h). This improvement in the SALL experiment is due to a decrease in excessive rainfall in the northwestern Pacific area near 20°N and SPCZ.

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**Fig. 5.** (a)–(d) Precipitation distribution (mm month$^{-1}$) for each experiment and (e)–(h) their differences (mm month$^{-1}$) from the CNTL case. Contour interval for the precipitation differences is 100 mm, starting from 50 mm. The zero line is omitted. In (a)–(d) dark shading designates the values greater than +50 mm, and light shading denotes the values smaller than −50 mm.
sequently, the SALL experiment over the western Pacific leads to a better representation of the large-scale circulation as a combined effect of the three modifications, so that it shows a considerable improvement in the simulation of the precipitation. On the other hand, the SALL experiment tends to overestimate rainfall over the eastern Pacific. However, according to Xu et al. (2004), the rainfall amount of the CMAP data over the eastern Pacific tends to be underestimated when compared with the microwave imager data from the high-resolution Tropical Rainfall Measuring Mission (TRMM) satellite. If we consider this uncertainty to be included in the CMAP data, the excessive rainfall simulated in the model over this region is probably not a serious drawback.

2) Large-scale fields

From the discussion in section 4b(1), it is evident that the revised parameterization method of the moist convection scheme (i.e., the SALL experiment) improves the precipitation pattern. Here, we investigate the role of each component included within the revised convective parameterization method in changing the large-scale fields.

Figure 6 shows the distinctions in the zonal mean temperature and relative humidity between the CNTL and other experiments. First, it is apparent from Fig. 6a that the STCP run results in a moistening in the upper troposphere near the 300-hPa level over the Tropics. This moistening is due to the increase in detrainment in the lower level by the random selection of the cloud top over the Tropics, and moisture transport by large-scale circulation. Note that the detrainment of water vapor occurs only at the cloud top in the SAS scheme. The cloud top in the control SAS scheme is about 200 hPa over the Tropics, on average, whereas it varies down to the midtropospheric level. Enhanced longwave heating below the clouds in the STCP run would reduce the moistening effect in the midtroposphere, resulting in a moistening effect confined in the upper troposphere. Also, the STCP experiment shows moister air in the lower atmosphere below the 700-hPa level in the Southern Hemisphere, which is presumably related to the enhanced evaporation of falling raindrops as the falling raindrops pass the warmer midtroposphere. Note that the SAS scheme considers the evaporation of falling raindrops in addition to the moist downdrafts. Overall, the vertical profile of the moisture difference in the seasonal simulation is generally consistent with the result of the STCP case in the SCM framework over the Tropics. Meanwhile, in relation to the change in the meridional circulation, an asymmetric distribution of the moisture difference occurs in the Northern and Southern Hemispheres.

Corresponding to the change in the moisture distribution, a decrease and an increase in temperature appear in the upper troposphere and in the middle atmosphere, respectively, in the simulated STCP case (Fig. 6e). The changes in the temperature field simulated in the STCP experiment can be primarily interpreted as environmental adjustment processes induced by convection; the cooling (warming) in the upper (middle) troposphere is related to the change in moisture profile due to change in detrainment level in the STCP case. However, the excessive warming in the midtroposphere can be closely related to the radiative warming effect. Figure 7 shows that in the STCP experiment, the high- and low-level cloud amounts increase, whereas that of the midlevel clouds decreases. An increase in the high-level cloud amount with an increase in detrainment results in upper-air cooling by shortwave reflection and outgoing longwave emission, whereas it induces midlevel warming by downward longwave radiation. Therefore, it is apparent that the vertical distribution of the temperature difference is closely related to the changes in the cloud amount.

Moreover, in contrast to the results obtained with the SCM test bed, the impact of the convective momentum transport is not negligible. The features of the CMTP case are different from those of the CNTL case and the STCP experiment (Figs. 6b,f). It can be observed that in the CMTP case, the differences in the temperature and moisture are significant in the midlatitudes of the upper-tropospheric atmosphere, whereas the impact in the STCP case is distinct in the equatorial regions. In the CMTP case, cooling is distinct in the upper troposphere, and weak moistening occurs associated with the upper-air cooling. According to some previous studies (e.g., Gregory et al. 1997), it is obvious that the convective momentum transport has a significant impact on the zonal and meridional flow during the northern summer. Gregory et al. (1997) showed that the introduction of convective momentum transport reduces a large error in the tropical upper troposphere. Figure 8 clearly shows that in the CMTP case, the zonal and meridional winds are decelerated in the tropical upper troposphere, thereby affecting the large-scale circulation. In particular, the CMTP case exhibits a weakening of the Hadley circulation (see Fig. 8f). This weakening of the meridional circulation directly produces less heat transport toward the ITCZ; furthermore, it leads to large differences in the temperature and moisture in the upper troposphere (see Fig. 6f). This feature is probably due to the less transport toward the midlatitude and is also presumably due to a decrease in adiabatic
Fig. 6. Zonal mean differences between the CNTL experiment and other experiments for the (a)–(d) relative humidity (%) and (e)–(h) temperature (K). Dark shading designates the values greater than +5% in RH and +0.5 K in temperature. Light shading designates the values less than −0.5% and −0.5 K.
warming in the sinking branches of the meridional circulation.

On the other hand, the impact of the LSDP alone on the large-scale field as well as precipitation is not evident (cf. Figs. 6c,g), as analyzed in the SCM test bed. Finally, it is clear that the differences in the temperature and moisture fields in the SALL case are very similar to those in the STCP case (see Figs. 6d,h). This implies that the randomly determined cloud top is the most sensitive factor among the modifications. However, it is also evident that the other modifications are nonlinearly combined in the SALL case; consequently, the revised SAS scheme leads to an improvement in the precipitation pattern due to the intensification of the western Pacific ITCZ.

3) LARGE-SCALE CIRCULATIONS

As discussed in Donner et al. (2001), the differences in the structure of the cumulus parameterization heat source result in different structures in the total diabatic heating field, which leads to differences in the dynamics of the large-scale circulation. To further clarify the change in the large-scale circulation due to the modifications in the parameterization introduced in this study, the wind differences at the 200- and 850-hPa levels are represented in Fig. 9. It is clearly observed that the equatorial easterlies are weakened at the 200-hPa level in all the experiments excluding the LSDP case. The STCP and CMTP experiments show a similar pattern over the western Pacific, where a convergence area ap-

**Fig. 7.** Latitudinal differences of the STCP case from the CNTL run in zonally averaged cloud fraction (%). The solid line, line with plus signs, and line with open circles indicate each cloud fraction for the high-level cloud (above the 400-hPa level), the midlevel cloud (from the 700- to 400-hPa level), and the low-level cloud (below the 700-hPa level), respectively.

![Fig. 8.](attachment:image.png) Latitude–height cross section of (a)–(c) the zonal wind (m s$^{-1}$) and (d)–(f) the meridional wind averaged for the latitudinal band. (a), (d) The observation (RA2); (b), (e) the CNTL case; and (c), (f) the CMTP experiment. Contour intervals are 5 m s$^{-1}$ in the zonal wind and 0.5 m s$^{-1}$ in the meridional wind. Dark shading denotes the values greater than +5 (+0.5) m s$^{-1}$, and light shading denotes the values smaller than −5 (−0.5) m s$^{-1}$.
Fig. 9. The wind field of the CNTL case at (a) the 200- and (b) the 850-hPa level, and the differences (m s$^{-1}$) from the CNTL experiment at the (b)–(e) 200- and (g)–(j) 850-hPa level for each experiment. Contours and shading in (b)–(e) and (g)–(j) denote the convergence area ($10^{-6}$ s$^{-1}$) calculated by their wind differences. The contour interval is $1 \times 10^{-6}$ s$^{-1}$. The zero line is omitted. Dark (light) shading denotes the convergence (divergence) area.
pears because of the weakening of the upper-level easterlies. The STCP experiment shows a slight intensification of the low-level easterlies over the equatorial central Pacific, resulting in some degree of convergence near the Maritime Continent. However, the CMTP case only shows a deceleration of the low-level winds, so that a divergence area appears over the western Pacific. On the other hand, the SALL case shows very distinct latitudinal differences as a result of the nonlinear combination of the two above-mentioned modifications. An intensification of the low-level southeasterlies over the central Pacific area results in a wide convergence area along the ITCZ; this is similar to the STCP case. A deceleration of the low-level westerlies over the northwestern Pacific area is observed in both the SALL experiment and the CMTP case.

A change in the large-scale circulation is clearly detected by a change in sea level pressure (Fig. 10). When compared with the observation, all the experiments have negative biases on the sea level pressure in general. It is clearly observed that the SALL experiment tends to reduce this error. When compared with the CNTL case, the meridional circulation in the SALL run is considerably improved, representing an intensification of the Hadley cell and an indirect circulation in the midlatitude. A distinct feature in Fig. 10a is the southward shift of the Hadley circulation when convective momentum transport is active. In this study, the inclusion of convective momentum transport results in a southward shift as well as the weakening of the meridional circulation. Meanwhile, the change in the zonal flow in each experiment is not large, except in the CMTP case (Fig. 10b). The CMTP case shows a higher pressure over the western Pacific as compared to the other experiments. This implies less convection over the western Pacific due to the weakening of the low-level moisture convergence.

4) NONLINEAR INTERACTIONS

In section 4b(3), it was clarified that the STCP and CMTP experiments have a considerable influence on the model climate, whereas the LSDP experiment does not appear to play an important role in improving global precipitation and the associated large-scale circulation. An additional experiment was performed in order to investigate the role of the large-scale destabilization processes in the revised SAS scheme. Furthermore, the effect of the nonlinear interaction between the LSDP and other processes will be described in this section. The additional experiment is entitled “NLSD,” and it consists of five-member ensemble runs with the STCP and CMTP parameterizations excluding the LSDP modification for 3-yr summers.

In Fig. 11, as compared with the SALL experiment, there is an obvious decrease in the tropical precipitation along the ITCZ in the NLSD experiment. Moreover, the sensitivity of simulated precipitation in the NLSD experiment is degraded significantly in terms of the pattern correlation coefficient whose value is 0.69, which is otherwise 0.75 when the revised large-scale destabilization effect is included. In Fig. 11, it is easily observed that a dry tongue penetrates the Indonesian area over the western Pacific such that the rainfall is reduced considerably as compared to that of the observation. On the other hand, the precipitation in the NLSD case tends to increase in the SPCZ.

With regard to the large-scale fields, the zonal differences in relative humidity and temperature in the NLSD and the CNTL experiments are shown in Fig. 12. In comparison to the SALL case in Fig. 6, it is obvious that the NLSD experiment leads to a distinct decrease in the low-level moisture over the Tropics. Furthermore, for temperature, the difference is evident in the lower layer below the 700-hPa level. It is clear that the NLSD run has an exactly combined feature with the STCP and CMTP parameterizations from Figs. 6 and
However, it is important to note the difference between the SALL and NLSD experiments. From Fig. 12, it is certain that the large-scale destabilization process controls the large-scale circulation due to its nonlinear processes. The latitudinal differences in moisture and temperature between the SALL and NLSD cases suggest that the change in the meridional circulation occurs due to the difference in the large-scale destabilization effect. To clarify this point, the sea level pressure over the tropical region is investigated for these two experiments, as shown in Fig. 13. The NLSD experiment shows a higher pressure over the eastern and central Pacific areas as compared to the SALL case. This can lead to an enhanced tropical Walker circulation. However, the meridional circulation is clearly shifted southward in the NLSD case, although its strength remains unchanged.

An examination of the changes in the sea level pressure shown in Figs. 10 and 13 reveals that the inclusion of the revised large-scale destabilization, along with the other two components, prevents the southward displacement of the Hadley circulation, which is forced by the convective momentum transport. Owing to a more significant contribution of the revised large-scale destabilization in the SAS scheme, we speculate that the revised destabilization method considers the synoptically organized dynamic forcing that is also directly affected by the convective momentum transport.

5. Concluding remarks

This study describes a revised approach for the subgrid-scale convective properties in a cumulus convection scheme and evaluates its effects on a simulated model climate. The subgrid-scale convective processes tested in this study comprise three components: 1) the random selection of cloud top, 2) the inclusion of convective momentum transport, and 3) a revised large-scale destabilization effect considering synoptic-scale forcing. Each component in this scheme has been
evaluated within an SCM framework forced by TOGA COARE data. The impact of the changes in the scheme on seasonal prediction has been examined for the boreal summers of 1996, 1997, and 1999.

In the SCM simulations, an experiment that includes all the modifications reproduces the typical convective heating and drying feature. The simulated precipitation during the simulation period is in good agreement with the observed precipitation. The biases of simulated temperature and moisture are slightly improved. The random selection process of the cloud top is found to effectively moisten and cool the upper troposphere, which leads to a lowering of the cloud top in the control scheme with the deepest cloud top. This effect induces drying and warming below the cloud-top level due to cloud–radiation feedback. However, the other two components in the revised scheme do not play a significant role in the SCM simulations.

On the other hand, the role of each modification component in the scheme is significant in the ensemble seasonal simulations. The random selection process of the cloud top preferentially plays an important role in the adjustment of the thermodynamic profile, and the change in the thermodynamic structure leads to an intensification of the tropical Walker circulation due to the strengthened low-level easterlies. The inclusion of convective momentum transport in the scheme weakens the large-scale circulation and changes the location of the ITCZ. It leads to an overall decrease in precipitation over the northwestern Pacific near 20°N. Finally, the impact of the revised large-scale destabilization process on the simulated climate is insignificant. However, it plays an important role in the modulation of the meridional circulation by preventing the southward displacement of the Hadley circulation, which is forced by the convective momentum transport, when this process is combined with the other processes.

Consequently, the experiment with all the modifications shows a significant improvement in the precipitation fields over the western Pacific. This improvement results from the combined effect of the three modifications for the convective processes accompanied with a change in the large-scale circulation associated with the meridional circulation. This indicates a nonlinear interaction between the physical processes in the model and the simulated climate.

![Relative humidity and temperature diagrams](image-url)
Furthermore, the revised large-scale destabilization method developed in this study is a unique approach for parameterizing the physical processes in atmospheric models. In other words, 1) unlike the conventional approach to the parameterization method, which utilizes pointwise information, the proposed approach utilizes spatial information, which is resolution independent, and 2) physical forcing is explicitly modulated by dynamical motion, which is more accurate than the physical processes in atmospheric models.

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APPENDIX A

Formulation for Adjustable Parameters in the Control SAS Scheme

The tunable parameters \( c_1 \) and \( c_2 \) are calculated using the cloud-base vertical velocity \( \omega \) in the control SAS scheme of the MRF as follows:

\[
c_1 = \frac{\omega - \omega_2}{\omega_1 - \omega_2},
\]

\[
c_2 = \begin{cases} 
1 - \left( \frac{\omega - \omega_1}{\omega_1 - \omega_2} \right) & \text{for } \omega \leq \omega_1 \\
1 & \text{for } \omega \geq \omega_2 \\
1 - \left( \frac{\omega - \omega_3}{\omega_3 - \omega_4} \right) & \text{for } \omega_1 \leq \omega \leq \omega_2 \\
1 & \text{for } \omega_4 \leq \omega \leq \omega_3
\end{cases}
\]  

(A2)

In Eqs. (A1) and (A2), \( \omega_n \) \( (n = 1, 2, 3, 4) \) represents the threshold values for the vertical velocity, which can be tuned by the horizontal resolution of the model. The parameters \( c_1 \) and \( c_2 \) are controlled by the intensity of the cloud-base vertical velocity; these parameters have smaller values in order that the large-scale destabilization amount can be increased when \( \omega \) is a strong updraft value, and vice versa.

APPENDIX B

Determination of Large-Scale Contribution \( f(x) \) in the Revised SAS Scheme

In Eq. (6), the large-scale moisture convergence (LSMC) \( x \) is represented as follows:

\[
x = \int_{P_{\text{cloud, top}}}^{P_{\text{sfc}}} \frac{\langle -\nabla \cdot q \nabla \rangle_p}{\Delta p} dp. \tag{B1}
\]

The LSMC is vertically integrated from the surface to the cloud-top level, and is normalized by the pressure difference \( \Delta p = P_{\text{cloud, top}} - P_{\text{sfc}} \). The term enclosed in brackets in Eq. (B1) indicates a horizontally weighted value at a pressure level. The weighted mean of the LSMC at an arbitrary grid point \( i \) is obtained as follows:

\[
\langle -\nabla \cdot q \nabla \rangle_i = \frac{\sum_{j=1}^{R} [w_{ij} \times (-\nabla \cdot q \nabla)]}{\sum_{j=1}^{R} w_{ij}}, \tag{B2}
\]

\[
w_{ij} = \exp \left( -\frac{r_{ij}^2}{R^2} \right) \quad \text{only for } r_{ij} \leq R. \tag{B3}
\]

Here, \( w_{ij} \) represents the weight of the grid point \( j \) with respect to the grid point \( i \), and \( r_{ij} \) is the distance between these two grid points. Also, the effective radius \( R \) is a tunable parameter to represent the area where the convective activity at the grid point \( i \) can be affected by the large-scale processes.

To determine several tunable parameters of \( R, a, b, \) and \( \Delta t \) in Eqs. (5), (6), and (B3), we used climatological data. The LSMC is calculated using the NCEP reanalysis-II data (Kanamitsu et al. 2002b) for 25 yr from 1979 to 2003, and precipitation is taken from the CMAP data (Xie and Arkin 1997) during the same period. First, to determine the tunable parameter \( R \), we examine the pattern correlation between the spatially averaged LSMC and the global precipitation pattern, and also investigate the change in the correlation coefficient due to the change of effective radius \( R \) in the spatial average of LSMC. According to the result (not shown), the global mean of the pattern correlation coefficient between LSMC and precipitation increases together when the effective radius \( R \) increases from 0 to 750 km. However, the increase in the effective radius over 750 km operates to slowly decrease their correlation coefficient. Therefore, the effective radius \( R \) in this study is set to 750 km so that the LSMC is highly correlated to precipitation.

Additionally, tunable parameters such as \( a, b, \) and \( \Delta t \) in Eqs. (5) and (6) are determined in order to effectively represent the convective activity as the amount of LSMC. The large-scale contribution function \( f(x) \) is bounded from 0 to 1 in Eq. (6). Figure B1 shows the \( f(x) \) values with different values of \( b \). Because the normalized \( x \) (i.e., \( x/a \)) represents the amount of LSMC, a larger value of \( x \) results in a greater amount of convection due to a smaller \( f(x) \) in Eq. (5). On the contrary, a
negative value of $x/a$ represents a sinking motion and results in less convection due to a larger $f(x)$.

Consequently, the parameter $a$ denotes the reference value for normalizing $x$, and it is set as $4 \times 10^{-8}$ s$^{-1}$. The parameters $a$ and $b$ are closely related to the large-scale moisture convergence fields. In this study, $b$ is set to 3.0 so that the LSMC $x$ maintains the typical value when active convection occurs in the model and that the large-scale contribution function $f(x)$ has values similar to that of the control case. The adjustment time-scale parameter $\Delta t$ is set to 30 min as the typical convection time scale because this value is less sensitive than the other parameters. We realize that parameters such as $a$, $b$, and $\Delta t$ in Eqs. (5) and (6) are still tunable, but they are physically determined based on a statistical analysis between the observed precipitation and large-scale features. As an example, the new scheme was able to reproduce subtropical precipitation in the western Pacific in a regional climate model with a horizontal resolution of about 50 km, which was not possible with the control SAS scheme (Yhang and Hong 2005).

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