METEOROLOGICAL APPLICATIONS
Meteorol. Appl. **17**: 287–297 (2010)
Published online 1 December 2009 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/met.169

A Dual-scheme approach of cumulus parameterization for simulating the Asian summer monsoon

Kim-Chiu Chow[a,b]* and Johnny C. L. Chan[a,c]
[a] *Laboratory for Atmospheric Research, Department of Physics & Materials Science, City University of Hong Kong, Hong Kong, China*
[b] *Department of Mathematics, Hong Kong University of Science & Technology, Hong Kong, China*
[c] *Guy Carpenter Asia-Pacific Climate Impact Centre, City University of Hong Kong, Hong Kong, China*

ABSTRACT: The objective of this study is to introduce a novel approach of applying cumulus parameterization schemes (CPSs) in regional climate models. In this approach, two CPSs are running at alternate time steps during time integration. The two common CPSs of Emanuel and Anthes-Kuo have been examined. The results presented suggest that this dual-scheme approach may enhance the performance of the model in simulating the Asian summer monsoon over East Asia, in comparison with the corresponding results by using any single CPS. This empirical study suggests that the dual-scheme approach can be considered as a potential alternative to the common ensemble approaches in short-term climate simulation or prediction. Copyright © 2009 Royal Meteorological Society

KEY WORDS cumulus parameterization; Asian summer monsoon; regional climate model; ensemble

Received 19 January 2009; Revised 22 June 2009; Accepted 14 August 2009

1. Introduction

To simulate the climate, one fundamental task of a climate model is to compute the flow field by solving a set of governing equations. Once the dynamic field is computed, the relevant physical processes will be treated, which are usually implemented by using some physical parameterization schemes. One very important and probably still uncertain physical parameterization in climate modelling is cumulus parameterization. If the flow field is favourable for convection to occur, the cumulus parameterization scheme (CPS) will try to parameterize the process and adjust the atmosphere to a quasi-equilibrium state. The adjustment will change the vertical profiles of temperature and moisture, and subsequently a change in the flow field, which in turn will determine the occurrence of convection. Such a two-way interaction between the flow field and convection implies that if the location and intensity of the convection cannot be properly parameterized, the accuracy of the calculated flow field will be degraded as time evolves. In fact, it has been shown in Hoskins and Rodwell (1995) that the observed tropical circulation can be reproduced well by using a prescribed column-integrated heating field in the atmosphere.

Although cumulus parameterization is very important to climate modelling, the physical process of cumulus convection is still not well understood and there exist a number of different common CPSs for climate modelling. Different CPSs may have different principles in parameterization of cumulus convection (see the discussion of Arakawa, 2004), and it is generally recognized that no single CPS works well for all regions and for all atmospheric systems. Tuning a particular CPS may help improve the performance at certain geographical locations and periods. However, convective precipitation could be associated with different physical processes with different scales and a particular CPS generally cannot parameterize all convective processes of different initiation mechanisms. For instance, convection processes in the tropics could be substantially different from those in the mid-latitude regions. This problem is particularly outstanding in climate modelling, in which model domains usually cover a huge area (global or continental scale). As an alternative to developing and tuning CPSs, some ensemble approaches have been devised recently, particularly for the purpose of seasonal climate prediction. Representative examples are the super-ensemble approaches of Krishnamurti *et al.* (2000a, 2000b) and Krishnamurti and Sanjay (2003), in which results are obtained from the ensemble of multiple models with multiple CPSs, or the ensemble of multiple CPSs by a single model. In these approaches, equal weight or different weights at different regions are applied to make the ensemble. Ensemble approaches have the advantage that they can combine the strengths of different CPSs in simulating convective precipitation of different natures. It can be anticipated that a better precipitation field can be obtained by these approaches. However, in these approaches the time evolution of the flow field is basically not improved because

* Correspondence to: Kim-Chiu Chow, Department of Mathematics, Hong Kong University of Science & Technology, Clear Water Bay, Hong Kong, China. E-mail: kchow@ust.hk

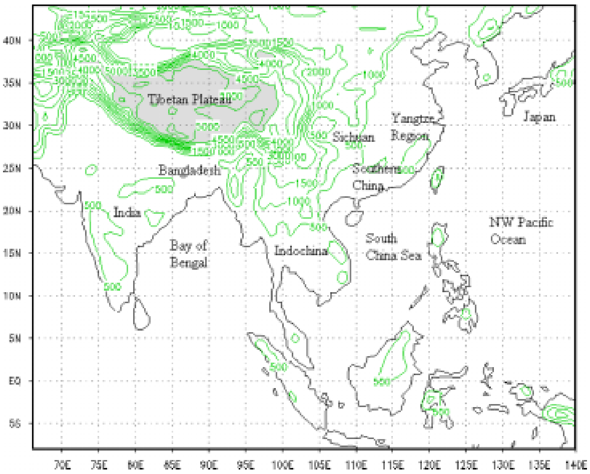

Figure 1. Domain of the regional climate model with the buffer zone excluded. The contours show the topography at 500 m interval and the shaded region depicts the region of the Tibetan Plateau with topography over 4500 m. Also shown are the names of some regions mentioned in this study. This figure is available in colour online at wileyonlinelibrary.com/journal/met

the better heating or temperature field associated with the better precipitation field is not fed back to the flow field during the time integration. This may not add an extra bonus to the overall performance of seasonal forecasting by the models.

Recently, Grell and Devenyi (2002) introduced a new approach in applying CPS. In their work, they devised an ensemble method to include different closures for the Grell CPS (Grell, 1993) at the time step when the CPS is called. In particular, different parameterizations of the cloud base mass flux used in various atmospheric models have been considered in their ensemble method (called dynamic control). Their scheme has the advantage that multi-model or model-scheme integrations as discussed previously are not required. Nevertheless, their parameterization framework is mainly based on the Grell CPS, and so in principal focuses on the kind of convection initiated due to instability.

The purpose of this study is to introduce a dual-scheme approach of cumulus parameterization for climate modelling. In this approach two different CPSs are used at alternate time step during the time integration. The two CPSs parameterize the cumulus process based on different principles (e.g. due to instabilities or moisture convergence): in other words, they have different strengths in cumulus parameterization. The motivation of this approach is based on the basic realization that if convective precipitation or convections can be better

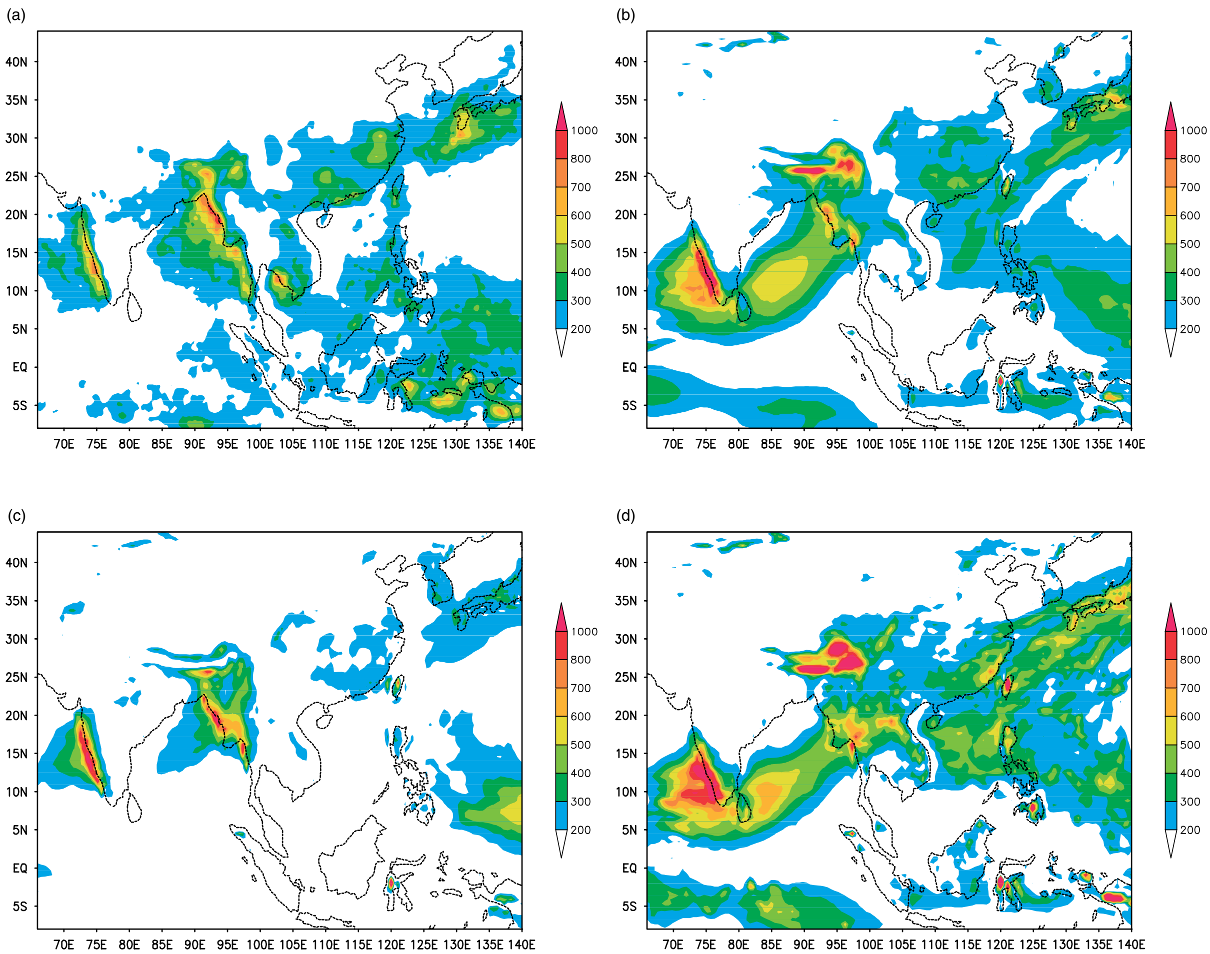

Figure 2. Mean total precipitation (mm) in June averaged for the five years 1998–2002. (a) TRMM data. (b) EXP_MIT_KUO. (c) EXP_KUO. (d) EXP_MIT. This figure is available in colour online at wileyonlinelibrary.com/journal/met

parameterized within the model domain at every time step, a better evolution of the flow field can be obtained. The improved flow field may in turn results in a better field of convections. This approach also has an advantage that no additional computing power is required compared with ensemble approaches.

The two CPS used in this dual-scheme approach are the Anthes-Kuo scheme (Anthes *et al*., 1987; KUO Scheme hereafter) and the MIT or Emanuel scheme (Emanuel, 1991; Emanuel and Zivkovic-Rothman, 1999; MIT scheme hereafter). The basic principle of the KUO scheme is to parameterize cumulus precipitation based on vertically integrated moisture convergence, while the MIT scheme parameterizes cumulus precipitation based on atmospheric instability in the vertical layers.

In this study, this dual-scheme approach is tested on a regional climate model (RCM) for simulating the Asian summer monsoon (ASM). The ASM affects a very large region in Asia during summer and brings plenty of rainfall to many Asian regions (Ding, 2004). In different regions and periods the precipitation associated with the ASM may have different initiation mechanisms, and may also have different scales of convection processes, which perhaps make the simulation of the ASM difficult. In this study the focus is on the simulation of the ASM in May and June. This is the period when the ASM first develops over the South China Sea (in May), and subsequently moves northward in June with a synoptic-scale Meiyu rainband well developed over China and Japan.

2. The numerical model and simulations

The RCM used in this study is RegCM3, developed at the Abdus Salam International Centre for Theoretical Physics and the US National Center for Atmospheric Research (Giorgi *et al*., 1993a, 1993b). The basic configuration of the RCM is similar to that used in Chow *et al*. (2006) with 18 vertical levels and a 60 km horizontal resolution. The span of the model domain, excluding the buffer zone for the lateral boundary conditions, is shown in Figure 1. The two CPSs used in the simulations are the KUO and MIT schemes. The modified version of the MIT scheme as described in Chow *et al*. (2006) is used in this study, in which some convection suppression criteria have been applied to reduce the substantial over-estimated precipitation over oceanic regions. The large-scale precipitation scheme described in Pal *et al*. (2000) is implemented in the RegCM3 to handle non-convective clouds and precipitation resolved by the model. The initial and lateral boundary conditions of the atmosphere are from the ECMWF ERA40 reanalyses, and the sea-surface temperature (SST) data are the Optimum Interpolation SST V2 weekly mean data obtained from the Climate Diagnostics Center of NOAA.

Three numerical experiments with the same configuration except CPSs have been performed by the RCM,

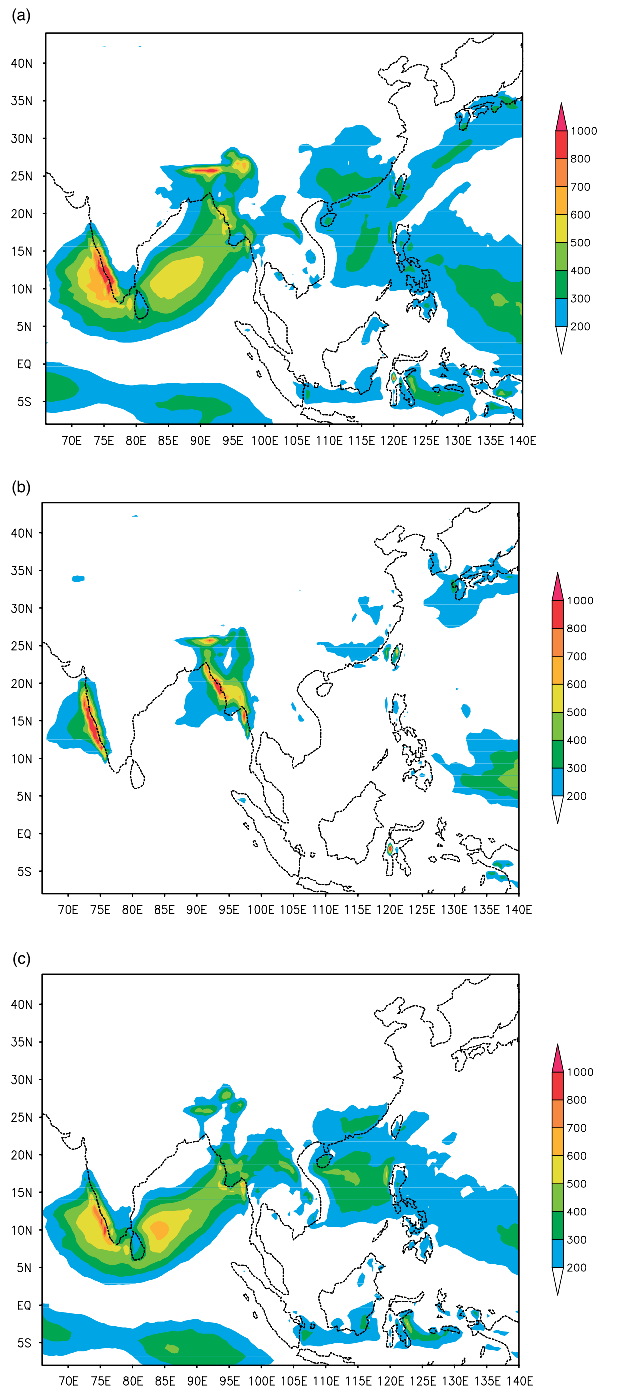

Figure 3. As in Figure 2 but for the convective precipitation of the three experiments in June. (a) EXP_MIT_KUO. (b) EXP_KUO. (c) EXP_MIT. This figure is available in colour online at wileyonlinelibrary.com/journal/met

- EXP_KUO – only KUO scheme is used;
- EXP_MIT – only MIT scheme is used;
- EXP_MIT_KUO – MIT and KUO schemes are used at alternate time steps.

The results of the experiments are evaluated using the precipitation data of the Tropical Rainfall Measuring Mission (TRMM), obtained from NASA. The data set 3B42 version 6 of TRMM has been used in

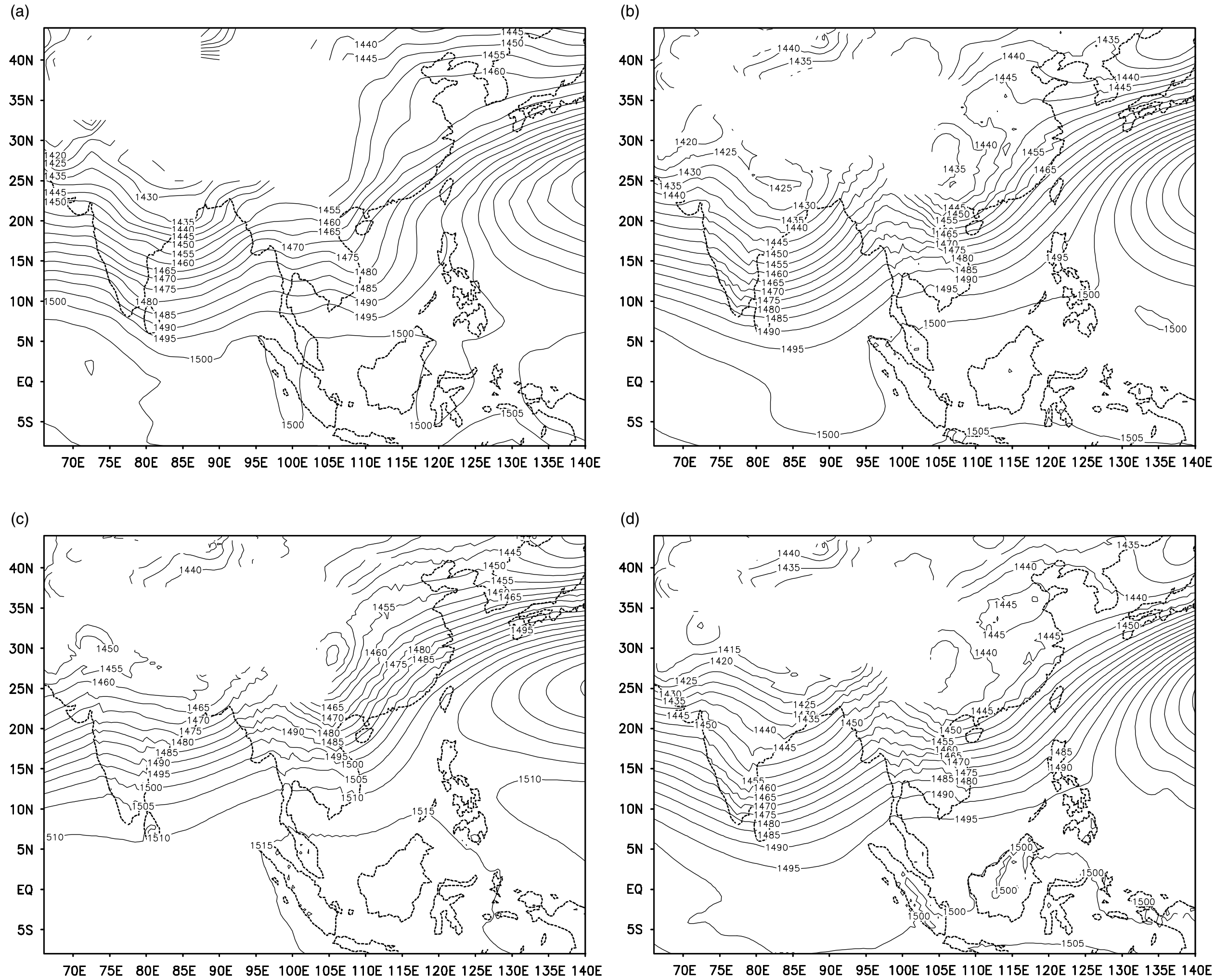

Figure 4. Mean 850-hPa geopotential height (m) in June averaged for the five years 1998–2002. (a) ERA40 data. (b) EXP_MIT_KUO. (c) EXP_KUO. (d) EXP_MIT. Contour interval is 5 mm.

this study, which has a 0.25° latitude × 0.25° longitude resolution. Considering that the availability of the TRMM data is from 1998 to present and the ERA40 data for the lateral boundary conditions is available up to 2002, the years 1998–2002 were chosen for the RCM experiments. In each experiment, the integration is from 1 April to 30 June and the 5 year climatology is obtained from the arithmetic mean of the results for these 5 years. The month of April is considered as the spin-up time for the RCM and the results will not be used.

3. Simulation results

The 5 year mean total precipitation fields in June simulated by the three experiments are compared with those of the TRMM data (Figure 2(a)). In general, EXP_KUO tends to underestimate the total precipitation over the East Asia region (Figure 2(c)), particularly over the major precipitation zones of Southern China (SC) and the Yangtze River region (YR; Figure 1). In addition, the total precipitation of the Meiyu rainband near Japan is also significantly underestimated. Nevertheless, it appears that the KUO scheme can simulate well the quantity and pattern of the precipitation associated with the Indian summer monsoon over the western coast of India and the eastern Bay of Bengal (BOB).

EXP_MIT (Figure 2(d)) tends to overestimate the total precipitation over most of the ASM region, particularly over the oceanic region as indicated in Chow *et al.* (2006). The regions with significant overestimated precipitation include the BOB and the western Arabian Sea near the western coast of India. In addition, the shape of the Meiyu rainband is not clearly simulated in EXP_MIT.

The dual-scheme approach of EXP_MIT_KUO (Figure 2(b)) shows a much better improvement in simulating the total precipitation field in terms of quantity and pattern. The performance of EXP_MIT_KUO is particularly good over East Asia. For example, the distinct precipitation zones such as those over SC, the YR and the Meiyu rainband are clearly simulated as in EXP_KUO with better quantity. The simulated precipitation over the oceanic region is also improved

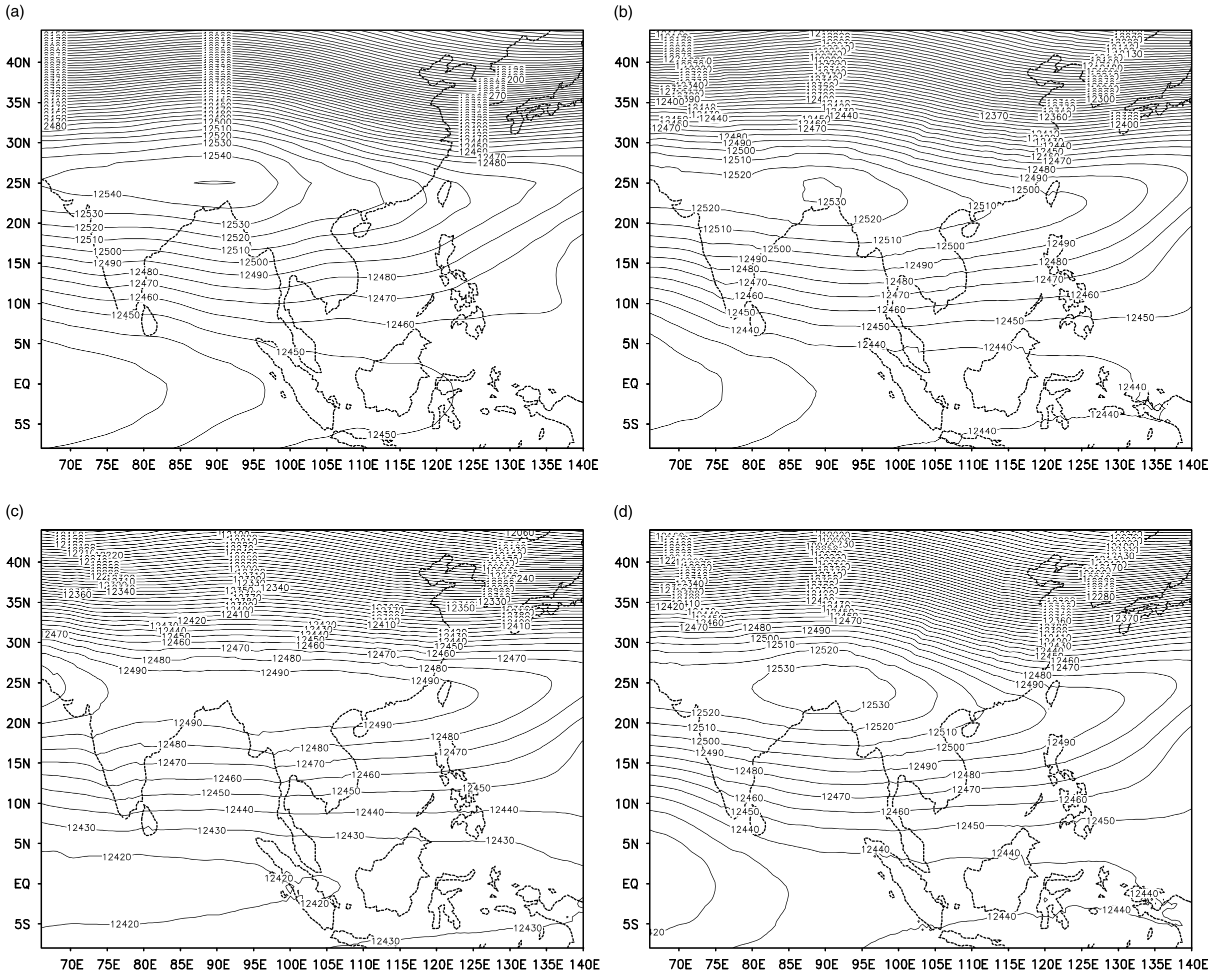

Figure 5. As in Figure 4 but for geopotential height at 200 hPa. (a) ERA40 data. (b) EXP_MIT_KUO. (c) EXP_KUO. (d) EXP_MIT.

in EXP_MIT_KUO. Unlike those underestimated in EXP_KUO and overestimated in EXP_MIT, the simulated precipitation over the northern SCS and the Northwestern Pacific ocean in EXP_MIT_KUO are closer to those in TRMM (cf. Figure 2(a) and (b)). The simulated precipitation band over the equatorial region between 70 and 100 °E is also improved in EXP_MIT_KUO. Despite these significant improvements, the precipitation fields of EXP_MIT_KUO over the BOB and the western Arabian Sea near India are still overestimated as in EXP_MIT.

To see how the CPSs perform in the three experiments, it is better to examine the simulated monthly mean convective precipitation. This is the part of precipitation simulated by the CPSs and is equal to the difference between the total precipitation and the precipitation simulated by the large-scale precipitation scheme.

The convective precipitation field in EXP_KUO (Figure 3(b)) is very similar to that of the total precipitation (Figure 2(c)), showing that the precipitation contributed by the large-scale precipitation scheme is small. This is reasonable because the basic principle of the KUO scheme is to parameterize the precipitation due to large-scale moisture convergence. The large-scale precipitation scheme plays a similar role in the RCM and so its effect is small in EXP_KUO. The situation in EXP_MIT is different from that of EXP_KUO in which the precipitation over the YR and the Meiyu rainband are mainly contributed by the large-scale precipitation (cf. Figures 2(d) and 3(c)). This is because these precipitations are mainly due to large-scale moisture convergence, but the MIT scheme mainly deals with the precipitation associated with the instabilities of the atmosphere. The convective precipitation field simulated by the dual-scheme approach (Figure 3(a)) shows a mixture of the KUO and MIT schemes. It is important to note that the convective precipitation field in EXP_MIT_KUO is not simply the average of those in EXP_KUO and EXP_MIT. For instance, the values of the convective precipitation in some regions such as the Meiyu rainband and southern China are larger than that of EXP_KUO and EXP_MIT. In addition, the precipitation over some oceanic regions such as those over the western BOB and the equatorial region in EXP_MIT_KUO are not significantly less than those in EXP_MIT.

The simulated 5 year mean 850 hPa geopotential height fields in June are compared with those from the ERA40 data (Figure 4(a)). The 850 hPa geopotential heights are generally higher in EXP_KUO over the model domain (cf. Figure 4(a) and (c)). On the other hand the

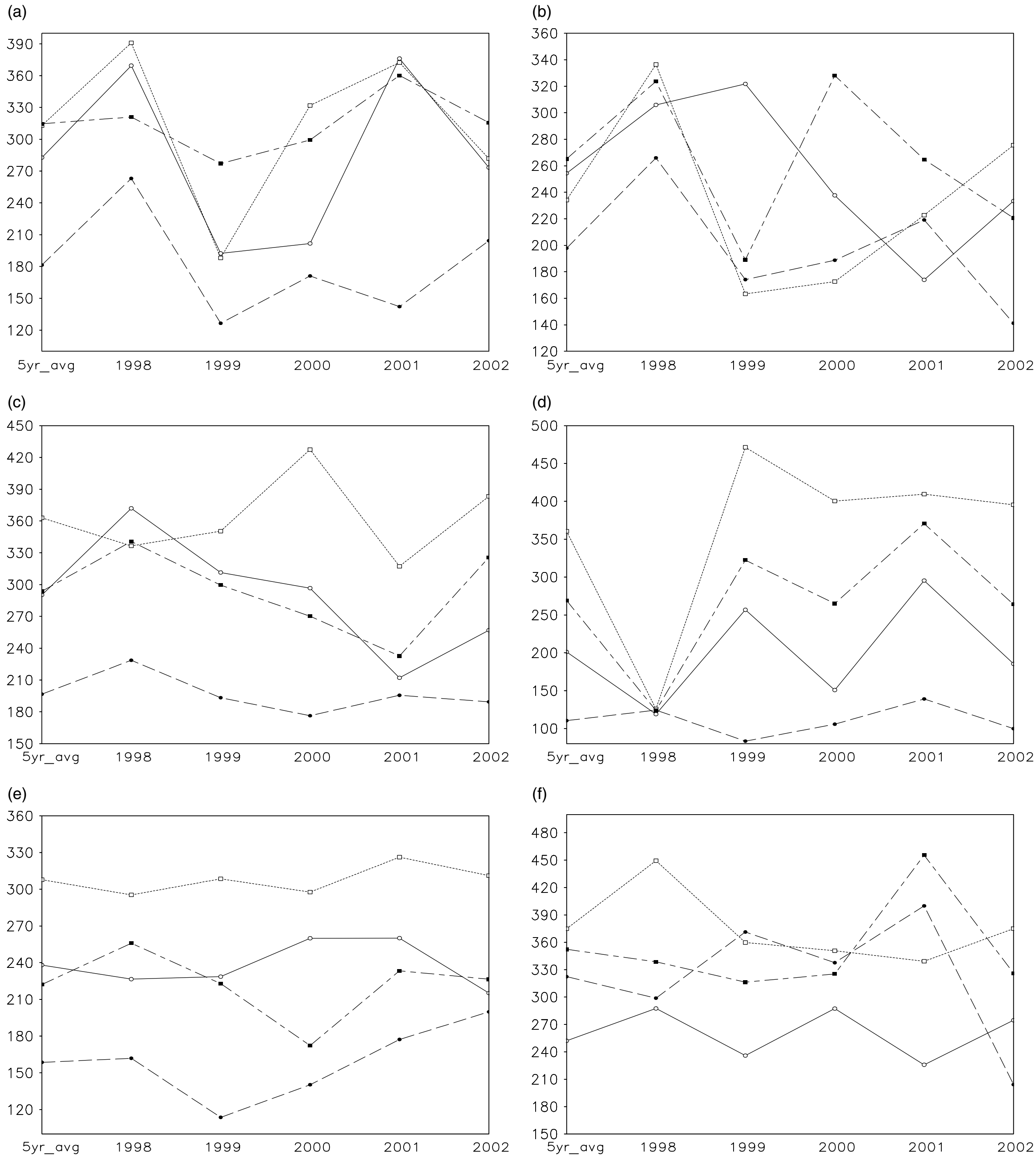

Figure 6. Five-year (1998–2002) mean and variation of total precipitation (mm) in June averaged over various regions. (a) South China (108–118 °E, 20–27°N). (b) Yangtze River region (110–120 °E, 28–33°N). (c) Japan (125–140 °E, 25–35°N). (d) South China Sea (110–120 °E, 10–20°N). (e) Indochina Peninsula (95–110 °E, 10–20°N). (d) India Peninsula (70–80 °E, 10–20°N). TRMM KUO MIT MIT+KUO.

850 hPa geopotential height field simulated in EXP_MIT (Figure 4(d)) is closer to that of the ERA40 data in terms of magnitudes and pattern. The 850 hPa geopotential height field in EXP_MIT_KUO (Figure 4(b)) is very similar to that of EXP_MIT, but with the magnitudes and pattern even closer to that of the ERA40 data. The KUO scheme has been criticized for excluding shallow clouds or shallow convections (e.g. Raymond and Emanuel, 1993), and so the KUO scheme is recommended to be used together with another scheme for shallow clouds (Arakawa, 2004). In the dual-scheme approach, shallow convections, in principle, are better resolved by the MIT scheme and it might explain the better 850 hPa geopotential height field simulated in EXP_MIT_KUO.

The corresponding mean geopotential height fields at 200 hPa simulated in the three experiments (Figure 5) show similar characteristics as those at 850 hPa. Compared with the other two experiments, the KUO scheme

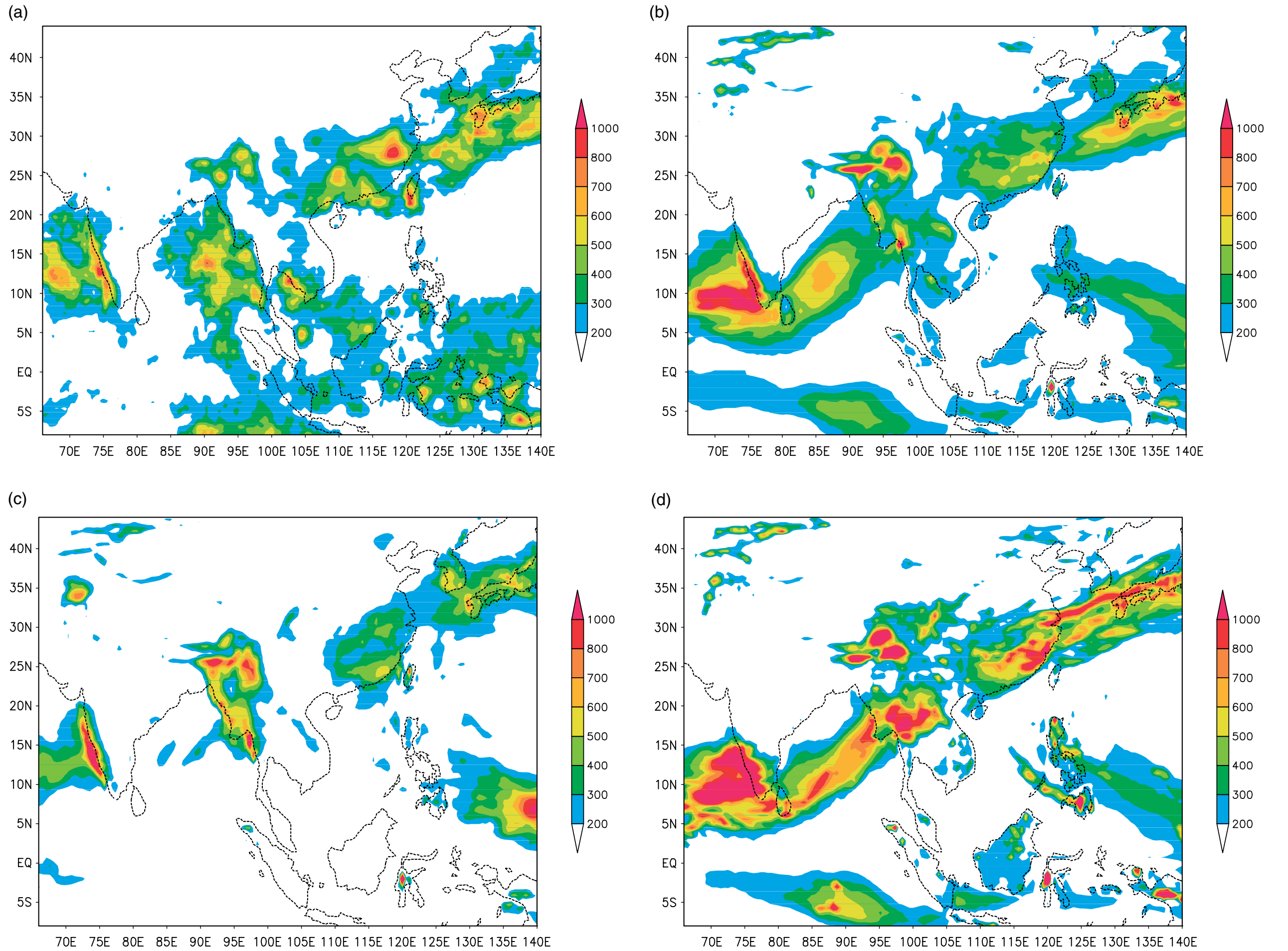

Figure 7. As in Figure 2 but for the year 1998. (a) TRMM data. (b) EXP_MIT_KUO. (c) EXP_KUO. (d) EXP_MIT. This figure is available in colour online at wileyonlinelibrary.com/journal/met

does not reproduce well the upper tropospheric geopotential height of the ERA40 data (cf. Figure 5(a) and (c)). The values are generally smaller over the model domain, reflecting that the temperature of the atmosphere in EXP_KUO is generally cooler (figures not shown). The 200 hPa geopotential height fields simulated in EXP_MIT_KUO and EXP_MIT (Figures 5(b) and (d)) are very similar in magnitude and pattern. Nevertheless, the maximum value in the ERA40 data (Figure 5(a)) is still slightly underestimated in both experiments.

It has been shown that the dual-scheme approach of EXP_MIT_KUO is good at simulating the 5-year mean precipitation in June over the East Asia. The performance of this approach in individual years over different regions is also worth examining. Figure 6 shows the monthly-mean precipitation in June averaged over the regions SC (108–118 °E, 20–27°N), YR (110–120 °E, 28–33°N), Japan (125–140 °E, 25–35°N), SCS (110–120 °E, 10–20°N), Indochina Peninsula (95–110 °E, 10–20°N) and India Peninsula (70–80 °E, 10–20°N) for 1998–2001. Compared with the other two experiments, it appears that EXP_MIT_KUO can capture well the 5 year mean and interannual variations of the rainfall over the SCS (Figure 6(d)) and the Meiyu over Japan (Figure 6(c)). Although not as good as that over SCS and Japan, the interannual variation of rainfall over SC is still reasonably captured by the dual-scheme approach (Figure 6(a)), except that the substantially decrease in rainfall over SC in 1999 and 2000 is not well captured. The interannual variation of rainfall over the YR cannot be captured by all three experiments (Figure 6(b)), although the 5 year mean rainfall is reasonably simulated in EXP_MIT_KUO and EXP_MIT. The KUO scheme generally underestimates the amount of rainfall in the five years over all regions except the India Peninsula (Figure 6(f)). In fact, among the three experiments, the 5 year mean rainfall over the Indian Peninsula simulated by EXP_KUO is closest to that of the TRMM data. The interannual variation of rainfall over the Indochina Peninsula is relatively small (Figure 6(e)), and the 5 year mean rainfall simulated in EXP_MIT_KUO is closest to that of the TRMM data.

The performance of the dual-scheme approach can be further examined from some case studies. The monthly mean precipitation fields in June of 1998 and 2001 are shown in Figures 7 and 8. Regarding the rainfall of the summer monsoon over Eastern China and Japan (Meiyu), the years 1998 and 2001 can be considered as wet

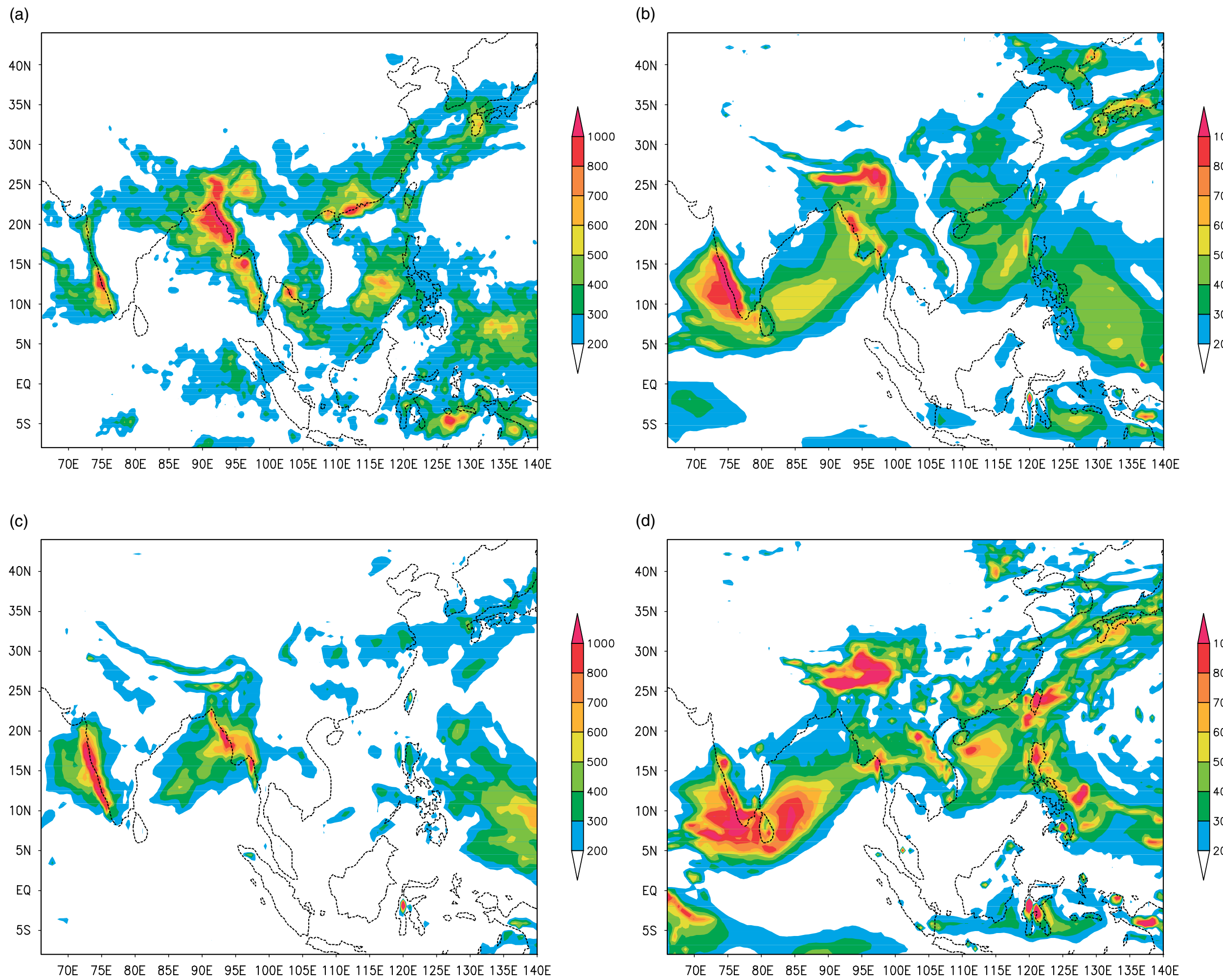

Figure 8. As in Figure 2 but for the year 2001. (a) TRMM data. (b) EXP_MIT_KUO. (c) EXP_KUO. (d) EXP_MIT. This figure is available in colour online at wileyonlinelibrary.com/journal/met

and dry years, respectively. This classification can be realized from the TRMM data (Figures 6(a) and (c)), as is also consistent with the classification in some previous studies (e.g. Liu *et al.*, 2006; Li and Ju, 2009). In June 1998, the anomalously large precipitation over the YR led to a severe flood in the region (Chan *et al.*, 2000; Ding, 2004).

In the wet year 1998, all three experiments can simulate above-mean precipitation over Eastern China and Japan (Figure 7). However, the distinct heavy precipitation zone over the YR (Figure 7(a)) is not well captured in all the three experiments. Despite this deficiency, the dual-scheme approach can simulate well the magnitude and pattern of the Meiyu rainband near Japan (Figure 7(b)). Similar to that of the 5 year mean, the patterns of the Meiyu rainband and precipitation over East Asia are not well simulated by EXP_MIT (Figure 7(d)).

In the dry year 2001, the below-mean precipitation over Eastern China and Japan can also be captured by all three experiments (Figure 8). However, the above-mean precipitation over the SCS and equatorial Northwestern Pacific Ocean (east of the Philippines) in this year can only be captured by EXP_MIT_KUO and EXP_MIT (Figures 8(b) and (d)). In fact, the performance of the KUO scheme in simulating the summer monsoon precipitation over SC and Eastern China for this year is generally poor (Figure 8(c)).

So far only the monthly mean precipitation has been discussed, and it is also important to see whether the time evolution of the simulated precipitation can be improved by using the dual-scheme approach. The performances of the three experiments in simulating the evolution of the ASM precipitation over SCS and Eastern China in May and June of the wet year 1998 have been examined (Figure 9). In this period the onset of the ASM occurred in late May over the SCS (so-called the SCS summer monsoon) and subsequently moved northward to the China mainland (Figure 9(a)). In EXP_KUO, while the precipitation over the YR in June can be reasonably simulated, the onset of the SCS summer monsoon in late May cannot be properly simulated (cf. Figures 9(a) and (c)). The situation in EXP_MIT is similar, although the amount of precipitation is generally larger (Figure 9(d)). The performance of EXP_MIT_KUO in simulating the evolution of the ASM precipitation in 1998 (Figure 9(b)) is again better than that of EXP_KUO and EXP_MIT. The

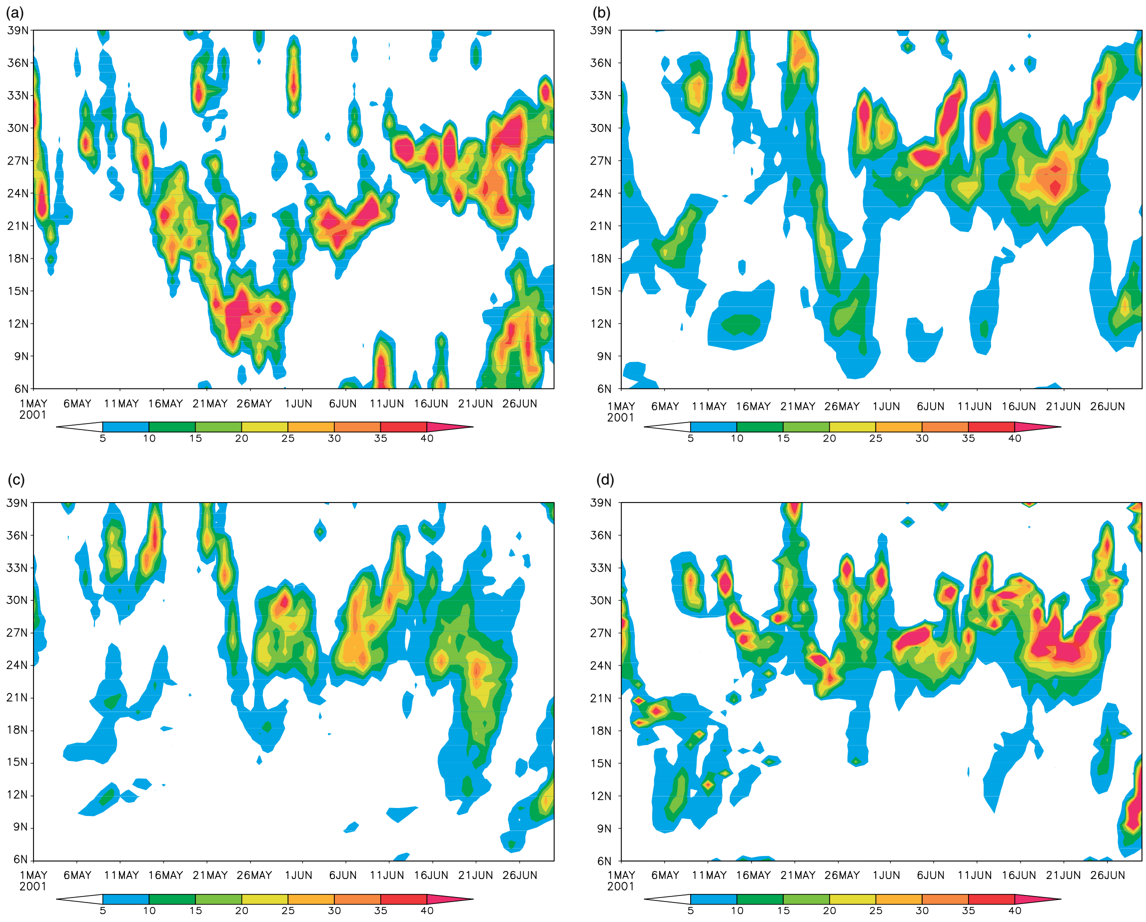

Figure 9. Time – latitude variation of total precipitation (mm day^{-1}) in May and June of 1998 averaged for the longitudes between 110 and 120 °E. (a) TRMM data. (b) EXP_MIT_KUO. (c) EXP_KUO. (d) EXP_MIT. This figure is available in colour online at wileyonlinelibrary.com/journal/met

improvement is most significant in May, in which the southward movement of the precipitation from the China mainland to the SCS can be captured by EXP_MIT_KUO (cf. Figure 9(a) and (b)) although the quantity of the precipitation is underestimated. In addition, the subsequent northward shift of the precipitation from the SCS during late May to early June can also be reasonably captured by this dual-scheme approach.

The corresponding results in the dry year 2001 (Figure 10) show that the dual-scheme approach is again better in simulating the evolution of the SCS summer monsoon in May and June. In particular, the southward evolution of the precipitation over SCS (about 15°N) around 23 May (Figure 10(a)) can only be captured by EXP_MIT_KUO (Figure 10(b)). This precipitation is basically associated with the onset of the SCS summer monsoon. In general, the precipitation over SCS in May 2001 is underestimated in both EXP_KUO and EXP_MIT (Figure 10(c) and (d)).

4. Discussion

The basic principle of the MIT scheme is to parameterize convections due to instabilities of the atmosphere. However, precipitation associated with large-scale moisture convergence is poorly resolved by this scheme and this task is basically done by the large-scale precipitation scheme. Basically, the large-scale precipitation scheme is to parameterize precipitation due to condensational processes at the grid points. For precipitation associated with large-scale moisture convergence, as in the case of the Meiyu rainband, the performance of the large-scale precipitation scheme is generally not good as shown in this study. Some model simulations (e.g. Huang *et al*., 2001; Lee *et al*., 2005) suggest that the KUO scheme is good at simulating the Meiyu precipitation of the ASM which is basically due to large-scale moisture convergence. The results of this study suggest that the role played by the KUO scheme is similar to that of the large-scale precipitation scheme in simulating the ASM, but has a better performance. To interpret the dual-scheme approach, one may consider that the MIT scheme is the main CPS that resolves the precipitation based on the related microphysics and instabilities of the atmosphere, while the KUO scheme is to parameterize the precipitation due to large-scale moisture convergence (just like calling the large-scale precipitation scheme).

The empirical results of this study suggest that the use of the dual-cumulus scheme approach may significantly improve the performance of the RCM in

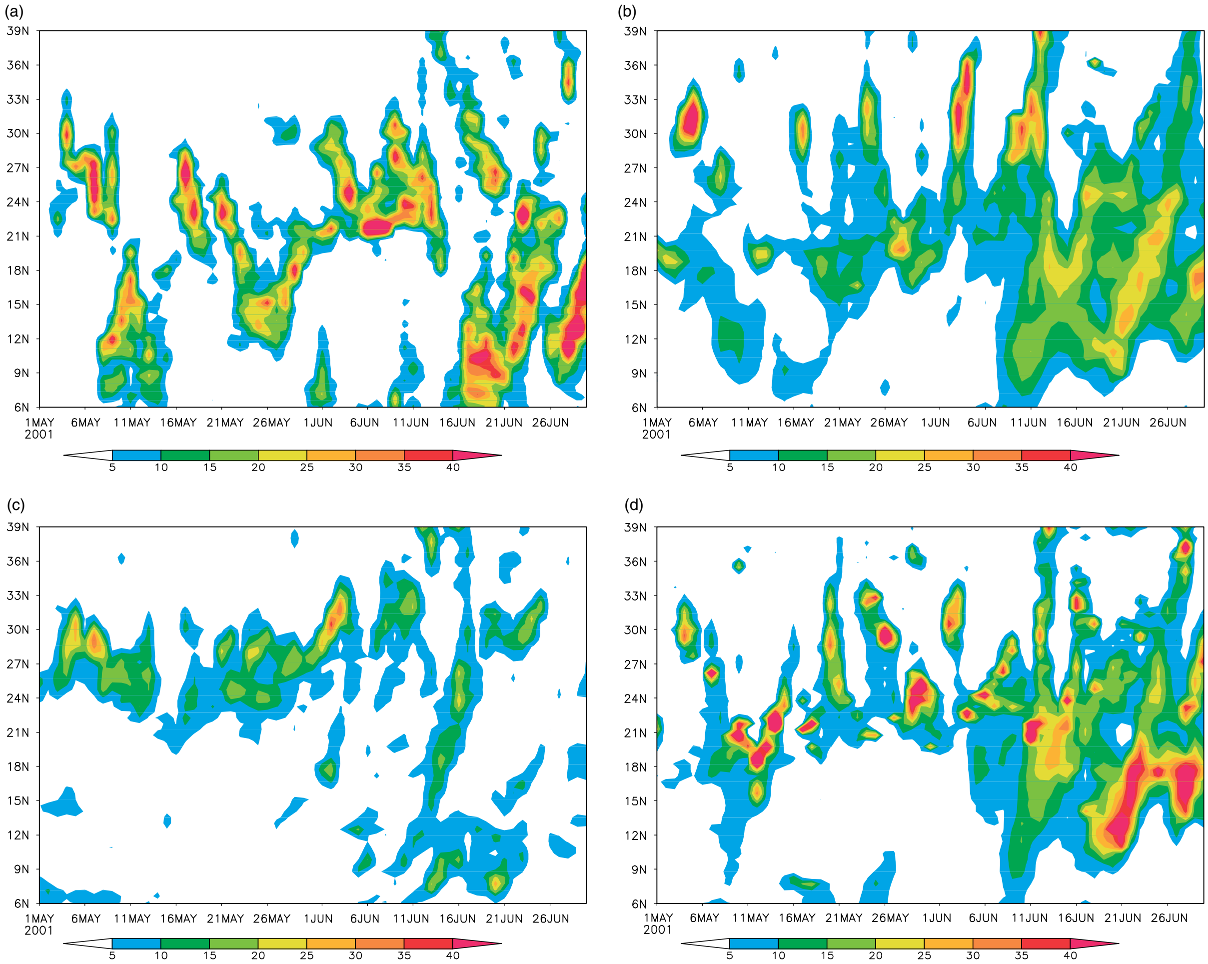

Figure 10. As in Figure 9 but for the year 2001. (a) TRMM data. (b) EXP_MIT_KUO. (c) EXP_KUO. (d) EXP_MIT. This figure is available in colour online at wileyonlinelibrary.com/journal/met

simulating the ASM precipitation and dynamic field during the Meiyu period in June, compared with the corresponding results by using the single CPSs of MIT and KUO. The resulting precipitation and dynamic fields are not simply the arithmetic means of the results by the two single-cumulus-scheme simulations, showing that this is not a linear combination of the two CPSs and convection and flow field are interrelated as discussed in Section 1. Since the ASM involves multiple scales of dynamics and physical processes (e.g. convection), the present results suggest that using a single CPS or physical parameterization (which usually developed for a particular scale or small range of scales) may be not enough to simulate the ASM realistically.

The better performance of this dual-scheme approach in simulating the ASM over East Asia is possibly related to the better heating field simulated by the RCM. At each time step during the time integration, when a CPS (e.g. KUO) is called, the condition of the atmospheric column at each horizontal grid point will be checked whether it is favourable for convection to occur based on the principle of that CPS (e.g. moisture convergence for KUO), and condensational heating will be evaluated if there is cumulus precipitation. The resulting vertical profile of heating will then used by the tendency equations of the RCM dynamic core to calculate the associated change in the flow field at the same time step. In the next time step, similar procedures repeat but with another CPS (e.g. MIT). At the grid points where condensational heating is generated by the two different CPSs at the two time steps, the effective heating can be simply considered as the averaged heating over this two-time-step period. The averaged flow field in this period should be dynamically consistent with this effective heating. By advection, the averaged flow field will change the distribution of some thermodynamic variables such as moisture and temperature, which in turn will affect the generation of condensational heating in the subsequent time steps. Therefore, the dual-scheme approach can be considered as making ensembles of the flow and heating fields for the two-time-step period and they are interrelated. It can be anticipated that if convections can be better parameterized within the model domain at every two time steps, a better evolution of the flow field can be simulated by the RCM.

It is worth mentioning that the main objective of this short study is to discuss and suggest an alternative idea of applying CPSs in climate models. The results presented here are indeed empirical and preliminary. For instance, although only two CPSs, KUO and MIT, have been tested for the dual-scheme approach in this study, it is possible that other combinations of CPS may also improve the performance of the RCM for different regions and periods. In addition, when implementing the dual-scheme approach, the CPSs can also be shifted every few time steps instead of at alternate time step. Therefore, to apply this idea in climate modelling some additional experimental work is needed to optimize the performance of this approach on the specific climate model. Finally, it is likely that this dual-scheme approach can be extended to use more than two CPSs with different basic principles. In this case, the dual-scheme or multiple-scheme approach is to a certain degree analogous to the existing ensemble approaches in seasonal forecasting.

Acknowledgements

This work was supported by City University of Hong Kong Grant 9610021.

References

Anthes RA, Hsie EY, Kuo YH. 1987. *Description of the Penn State/NCAR Mesoscale Model Version 4 (MM4)*. Technical Note NCAR/TN-282+STR. NCAR: Boulder, CO; pp 25–32.

Arakawa A. 2004. The cumulus parameterization problem: past, present, and future. *Journal of Climate* **17**: 2493–2525.

Chan JCL, Wang Y, Xu J. 2000. Dynamic and thermodynamic characteristics associated with the onset of the 1998 South China Sea Summer monsoon. *Journal of the Meteorological Society of Japan* **78**: 367–380.

Chow KC, Chan JCL, Pal JS, Giorgi F. 2006. Convection suppression criteria applied to the MIT cumulus parameterization scheme for simulating the Asian summer monsoon. *Geophysical Research Letters* **33**: L24709, DOI:10.1029/2006GL028026.

Ding Y. 2004. Seasonal march of the East-Asian summer monsoon. In *East Asian Monsoon*, Chang CP (ed.), World Scientific: Singapore; pp 3–53.

Emanuel KA. 1991. A scheme for representing cumulus convection in large-scale models. *Journal of the Atmospheric Sciences* **48**: 2313–2329.

Emanuel KA, Zivkovic-Rothman M. 1999. Development and evaluation of a convection scheme for use in climate models. *Journal of the Atmospheric Sciences* **56**: 1766–1782.

Giorgi F, Marinucci MR, Bates GT. 1993a. Development of a second-generation regional climate model (RegCM2). Part I: boundary layer and radiative transfer processes. *Monthly Weather Review* **121**: 2794–2813.

Giorgi F, Marinucci MR, Bates GT. 1993b. Development of a second-generation regional climate model (RegCM2). Part II: convective processes and assimilation of lateral boundary conditions. *Monthly Weather Review* **121**: 2814–2832.

Grell GA. 1993. Prognostic evaluation of assumptions used by cumulus parameterizations. *Monthly Weather Review* **121**: 764–787.

Grell A, Devenyi D. 2002. A generalized approach to parameterizing convection combining ensemble and data assimilation techniques. *Geophysical Research Letters* **29**: 38, DOI: 10.1029/2002GL015311.

Hoskins BJ, Rodwell MJ. 1995. A model of the Asian summer monsoon. Part I: the global scale. *Journal of the Atmospheric Science* **52**: 1329–1340.

Huang RH, Wu BY, Hong SG, Oh JH. 2001. Sensitivity of numerical simulations of the East Asian summer monsoon rainfall and circulation to different cumulus parameterization schemes. *Advances in Atmospheric Sciences* **18**: 23–41.

Krishnamurti TN, Kishtawal CM, LaRow T, Bachiochi D, Zhang Z, Williford CE, Gadgil S, Surendran S. 2000a. Multimodel ensemble forecasts for weather and seasonal climate. *Journal of Climate* **13**: 4196–4216.

Krishnamurti TN, Kishtawal CM, Shin DW, Williford CE. 2000b. Improving tropical precipitation forecasts from a multianalysis superensemble. *Journal of Climate* **13**: 4217–4227.

Krishnamurti TN, Sanjay J. 2003. A new approach to the cumulus parameterization issue. *Tellus* **55A**: 275–300.

Lee DK, Cha DH, Choi SJ. 2005. A sensitivity study of regional climate simulation to convective parameterization schemes for the 1998 East Asian summer monsoon. *Terrestrial, Atmospheric and Oceanic Sciences* **16**: 989–1015.

Li Y, Ju J. 2009. High-frequency transient and oscillation features related to wet and dry summer monsoon over East China. *Theoretical and Applied Climatology* **95**: 165–182.

Liu YM, Chan JCL, Chow KC, Ding Y. 2006. Ten-year climatology of summer monsoon over south China and its surroundings simulated from a regional climate model. *International Journal of Climatology* **26**: 141–157.

Pal JS, Small EE, Eltahir EAB. 2000. Simulation of regional-scale water and energy budgets: representation of subgrid cloud and precipitation processes with RegCM. *Journal of Geophysical Research* **105**: 29579–29594.

Raymond DJ, Emanuel KA. 1993. The Kuo cumulus parameterization. In *The Representation of Cumulus Convection in Numerical Models*. *Meteorological Monograph*, Vol. 46, American Meteorological Society: Boston, MA; 145–147.

