

# Structure variation dependence of tropical squall line on the tracer advection scheme in cloud-resolving model

Yuya Baba<sup>1</sup> and Keiko Takahashi

<sup>1</sup>*Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology,  
3173-25 Showa-mach, Kanazawa-ku, Yokohama 236-0001, Japan  
E-mail: babay@jamstec.go.jp*

**Abstract.** Two- and three-dimensional squall line experiments are performed using various kinds of tracer advection schemes in order to investigate response of deep convection structure to the applied tracer advection schemes. Vertical characteristics with the advection schemes are first analyzed in the two-dimensional cases. It is found that finite difference and high-order upwind schemes tend to overestimate rainfall amount by causing overshoot in computing the tracer advection. On the other hand, non-oscillatory scheme well suppresses the overshoot, and is found to be valid as vertical advection scheme. In the three-dimensional cases, horizontal characteristics depending on the tracer advection scheme are revealed. Non-oscillatory schemes, which are found to be useful for the vertical advection, cannot reproduce the sustainable squall line. Front line of the squall line consists of small convergence area where moisture is converted into the cloud water, and the cause of the failure is derived from the fact that the non-oscillatory scheme cannot capture the convergence area. In conclusion, the combination scheme consisting of the horizontal upwind and vertical non-oscillatory scheme is the best tracer advection scheme for simulating deep convection.

Key Words: Deep convection, Numerical Simulation, Tracer Advection Scheme, Nonhydrostatic Model

## 1. Introduction

Cumulus deep convection takes important roles in the transporting momentum, energy and moisture between sea surface and atmosphere. In order to improve numerical simulation of atmospheric circulation, various schemes for cumulus convection have been developed and proposed, however, the best scheme has not been determined yet.

The most important model components for simulating cumulus deep convection are believed to be cumulus convection or cloud microphysical schemes, which describe the convection involving conversion of water substances.

However, other model components are required for the simulation, and they might have significance on the behavior of cumulus deep convection and predictability. The model components considered to be important are dynamical core and tracer advection scheme for tracking water substances such as water vapor, cloud water and rain water.

Improvement of dynamical core for computing the moisture processes has been reported by Satoh (2003), and the model improvement has been applied to the some models. On the other hand, improvements due to the employment of advection scheme have been pointed out in various past studies.

Peng *et al.* (2003; 2005) implemented constrained interpolated profile (CIP) scheme into regional and global models, and found that the water vapor transport is improved by the applied advection scheme. Li *et al.* (2008) showed model conservation is improved using finite volume CIP schemes. Schroeder *et al.* (2006) employed essentially non-oscillatory (ENO) scheme to compute advection in general circulation model, and also reported some improvements. However, results using different advection schemes are not compared, thus the best scheme has not been specified yet by the previous studies. In addition, the advantages of the schemes have not been validated for cumulus deep convection using cloud-resolving model.

In this study, we will focus on the tracer advection scheme in simulating cumulus deep convection. Almost all commonly used advection schemes are selected, and the results are compared in two- and three-dimensional squall line experiments. Since the organized structure of the cumulus deep convection is important for simulating large-scale phenomena in meteorology, the significance on the formation of organized structure will be especially focused on.

## 2. Model descriptions

Model components used for this study are limited three components, namely dynamical core, cloud microphysical scheme and tracer advection schemes.

Dynamical core of atmospheric general circulation model named MSSG (Multi-Scale Simulator for the Geo-environment) is used to simulate dynamical part of the atmosphere (Baba *et al.* 2010a). The dynamical core employs Yin-Yang grid which consists of two identical latitude-longitude (lat-lon) grids. In the regional configuration, one of the two lat-lon grids is used for simulating regional atmospheric flows. The dynamical core employs fully compressible governing equations consisting of mass, momentum and energy conservation equations. The set of governing equations is solved by horizontal-explicit vertical-implicit (HEVI) scheme using 3<sup>rd</sup>-order Runge-Kutta method. Advection scheme for the dynamical core is fixed to 3<sup>rd</sup>-order upwind scheme of Wicker and Skamarock

(2002).

The cloud-microphysics of Grabowski (1998), which considers only 3 classes of water substances, is implemented into the MSSG model and is used for the present study. Ice phase water substances are diagnosed by atmospheric temperature, and effects of the ice phase except for latent heat of fusion are considered. Rainfall and snowfall are summed and computed as total rainfall amount.

The tracer advection schemes chosen for this investigation are UP1 (1<sup>st</sup>-order upwind scheme), CIP (semi-Lagrangian scheme; Yabe *et al.* 2001), WS3, WS5 (3<sup>rd</sup>- and 5<sup>th</sup>-order upwind schemes; Wicker and Skamarock 2002), WAF2 (2<sup>nd</sup>-order WAF scheme; Toro 1989), ENO2, ENO3 (2<sup>nd</sup> and 3<sup>rd</sup>-order ENO scheme; Shu and Oshert 1989). WAF2, ENO2 and ENO3 schemes are categorized into non-oscillatory schemes. It should be noted here that when the negative value appears in the computation of advection, the value less than zero is neglected but is not corrected during the computation.

### 3. Experimental setup

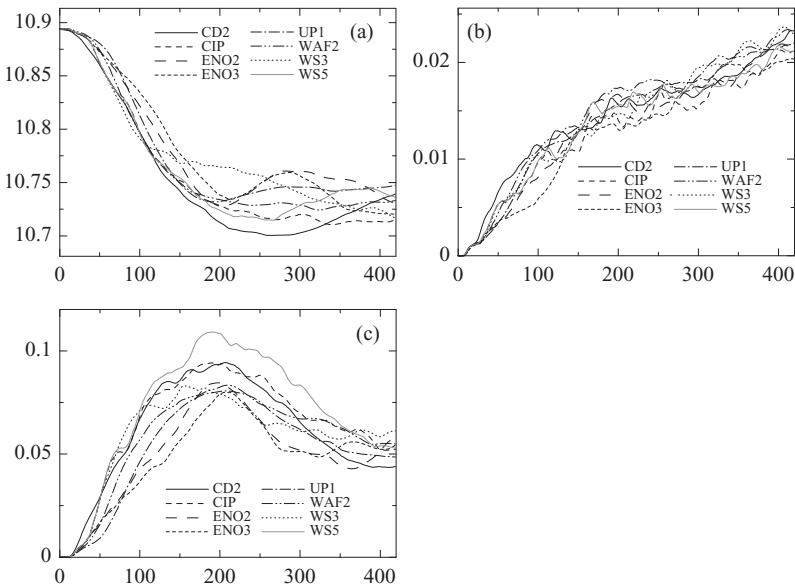
The experimental setup is based on Redelsperger *et al.* (2000). The initial atmospheric field's data is obtained from TOGA-COARE observation campaign. The vertical profiles such as pressure, potential temperature, humidity and wind speeds obtained from the data are interpolated in the initial model flow fields. The horizontal distributions are set to be homogeneous, thus flow fields setups for the two- and three-dimensional cases are identical.

Initial forcing for creating cold pool is given for the first 20 minutes, and the forcing is turned off after the 20 minutes. The squall line is expected to maintain for over 7 hours without any forcing. Horizontal domain size is 500 km x 375 km, and 20 km height is considered. Boundary condition of latitudinal direction is set to periodic, while the longitudinal directions are set to inlet and outlet conditions, respectively. Radiation, surface flux and turbulence schemes are turned off since these effects are not essential for simulating squall line's behavior (Redelsperger *et al.* 2000; Tomita 2008).

## 4. Results and discussion

### 4.1 Two-dimensional cases

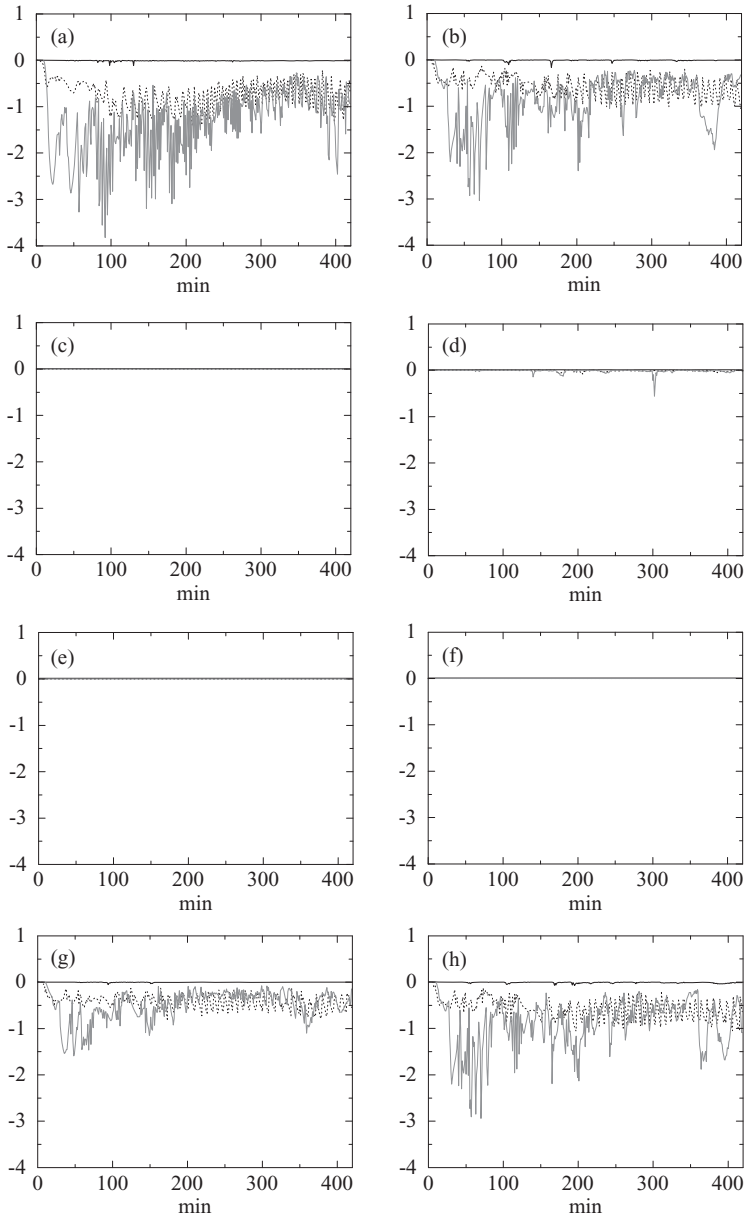
Two-dimensional cases are performed to investigate significance of the tracer advection schemes on the vertical motion of squall line. Our model can simulate two-dimensional squall line reasonably, and the simulated squall line maintains over 7 hours.



**Figure 1** Time variations of column-integrated water substances ( $\times 10^{-3} \text{kg m}^{-2}$ ) in two-dimensional cases. (a) Water vapor, (b) cloud water (and ice) and (c) rain (and snow).

Effect of difference in the advection schemes is investigated by analyzing trends of water substances. Statistics of the water substances, which are represented by column-integrated values, are compared in Figure 1. The time variations of water substances are different in each advection scheme. Time variation differences of water vapor and rain are found to be larger than those of cloud water. High-order upwind scheme and finite difference scheme (WS5 and CD2) show large water vapor consumption, and large production amount for rainfall. This fact means that these schemes tend to simulate strong convection. The trend is also found in the time variations of vertical wind speed (figure is not shown, but in Baba *et al.* 2010b), where WS5 and CD2 also show strong vertical wind speed.

If all advection schemes can simulate tracer advection correctly, results of different advection schemes must be identical. However, the results are actually different in each advection scheme. Therefore, the difference is considered to be derived from the characteristics of each advection scheme, i.e., artificial effect. When the discontinuous profile is advected by a certain numerical scheme, it is known that numerical oscillation occurs and it is used to cause both overshoot and undershoot. The mixing ratio of water substances must be a positive value since the value is a scalar variable, thus the oscillation might cause an unphysical effect on the convection.



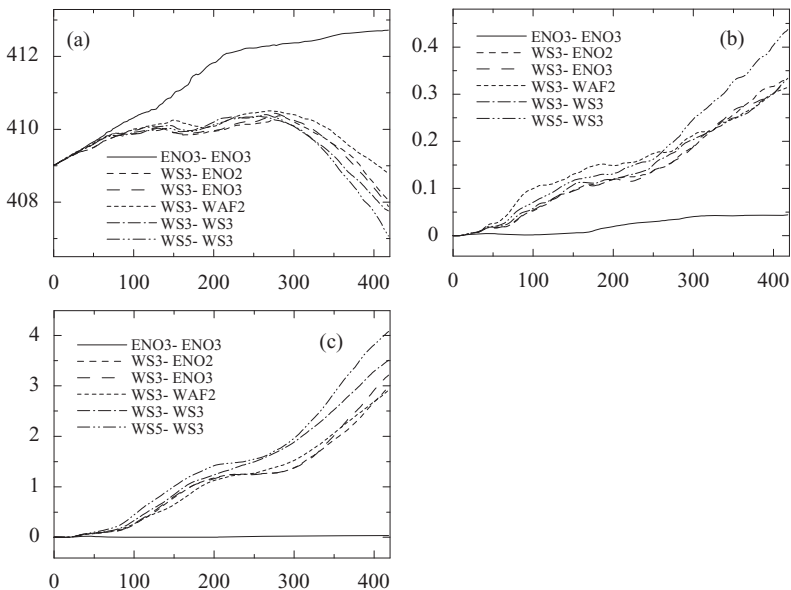
**Figure 2** Time variations of negative water substances ( $\text{kg m}^{-3}$ ). Black solid line: water vapor, black dot line: cloud water, gray solid line: rain water. (a) CD2, (b) CIP, (c) ENO2, (d) ENO3, (e) UP1, (f) WAF2, (g) WS3 and (h) WS5.

In order to investigate how the numerical oscillation is occurring, time variations of negative water substances are compared in Figure 2. Here, the negative value is regarded as the indicator of overshoot in water substances. It is found that negative values become large in the cases of CD2, CIP and WS5. The fact matches with the previous trends that CD2 and WS5 simulated too strong vertical convection and overestimated rainfall. In contrast, ENO2, ENO3 and WAF2 (non-oscillatory schemes) show sufficient small negative values, which indicates these schemes do not cause numerical oscillation, and that results in avoiding the overestimation.

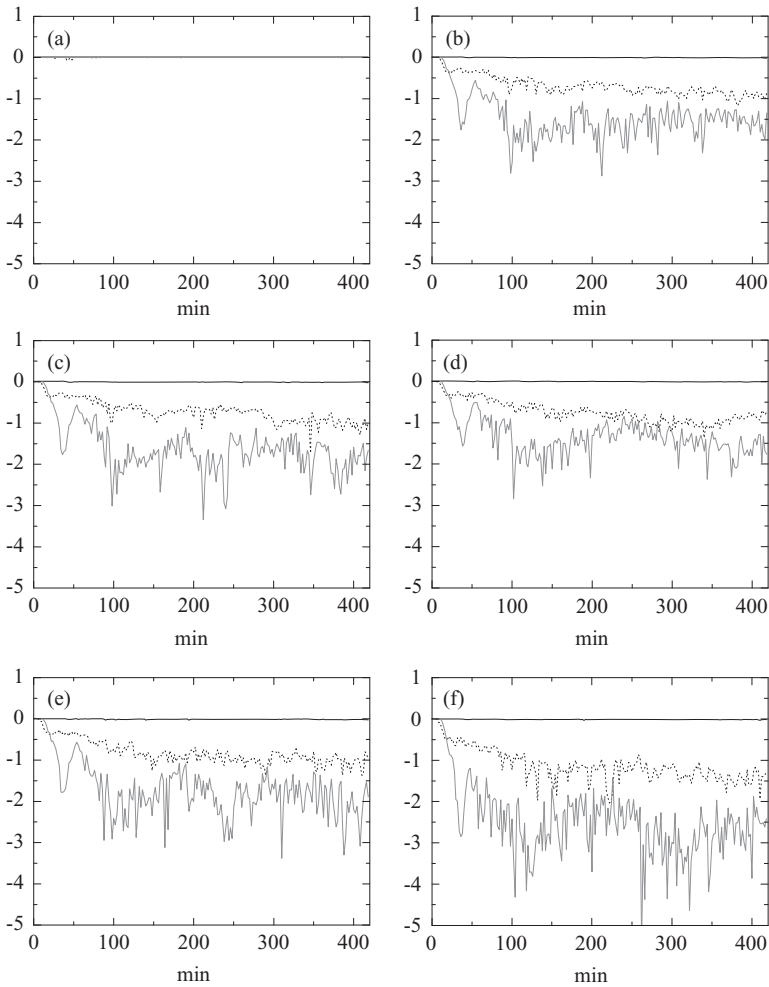
It is concluded that finite difference and high-order upwind schemes overestimate convection due to the large negative water substances, while non-oscillatory schemes can suppress the negative values, and thus can avoid the overestimation. In the latter three-dimensional analysis, these non-oscillatory schemes are basically used in the vertical direction.

#### 4.2 Three-dimensional cases

Three-dimensional squall line experiments are conducted to investigate its scheme dependence especially on their organized structures. The selected vertical advection schemes are basically non-oscillatory schemes, which are found to be valid in two-dimensional investigation, while several schemes that showed



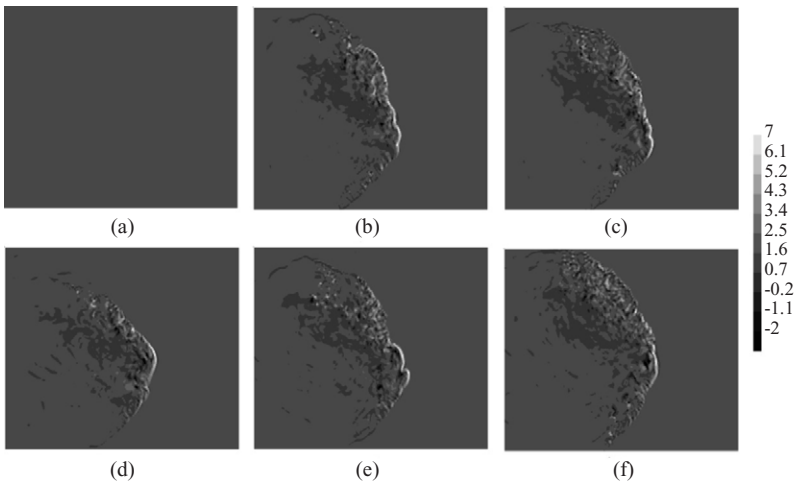
**Figure 3** Time variations of column-integrated water substances ( $\text{kg m}^{-2}$ ) in the three-dimensional cases. (a) Water vapor, (b) cloud water (and ice) and (c) rain (and snow).



**Figure 4** Time variations of negative water substances ( $\times 10^{-5} \text{kg m}^{-3}$ ). (a) ENO3-ENO3, (b) WS3-ENO2, (c) WS3-ENO3, (d) WS3-WAF2, (e) WS3-WS3 and (f) WS5-WS3.

relatively small negative values are applied as horizontal advection schemes.

As done in the two-dimensional cases, the time variations of column-integrated water substances are compared in Figure 3. All the cases show similar trends except for ENO3-ENO3, where ENO3 scheme is applied to the both horizontal and vertical directions. Since the water vapor is not consumed, and very small amount of both cloud and rain water are produced, it is considered that cumulus convection does not occur. The fact is also confirmed by the time



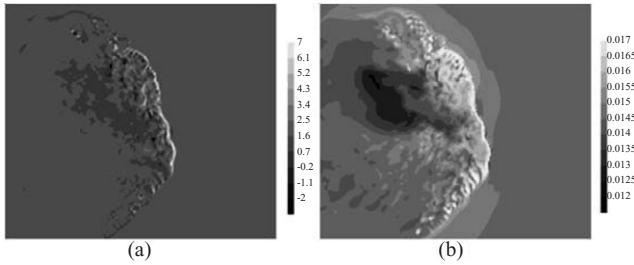
**Figure 5** Comparison of horizontal structure of squall line in the three-dimensional cases. Vertical wind speed ( $\text{ms}^{-1}$ ) distributions are compared. (a) ENO3-ENO3, (b) WS3-ENO2, (c) WS3-ENO3, (d) WS3-WAF2, (e) WS3-WS3 and (f) WS5-WS3.

variations of vertical wind speed (is not shown). Except for this case, other cases simulate almost same time variations of the water substances, but horizontally high-order upwind scheme slightly overestimates vertical convection as seen in Figure 3 (b) and Figure 3 (c).

Unphysical effect derived from the negative water substances is also investigated in these three-dimensional cases. The time variations of the negative water substances are compared in Figure 4. The negative values of ENO3-ENO3 show almost zero, but this should not be regarded as better results, since this case cannot simulate sustainable cumulus convection. Comparing the other cases, it is found that the negative value becomes larger as the order of the horizontal scheme becomes higher, as WS5-WS3 shows the largest negative value. This trend is not affected so much by the difference of the vertical schemes, but when the non-oscillatory scheme is applied as the vertical advection scheme, the negative value becomes small. Therefore it seems that vertical non-oscillatory scheme and horizontal upwind scheme is expected to work well as the tracer advection scheme for deep convection.

Organization of single convective cells in the squall line is an important feature for meteorology. Here, the organization of the convective cells is also expected, so the horizontal structures simulated by different schemes are compared in Figure 5. It is found that all squall lines have different horizontal structures only by the different tracer advection schemes. As noted above, the horizontal structure cannot be seen in ENO3-ENO3, since the case cannot





**Figure 6** Instantaneous horizontal structure at 700 m height at 7 hours in the case of WS3-ENO2. (a) Vertical wind speed ( $\text{m s}^{-1}$ ), (b) water vapor content ( $\text{kg m}^{-3}$ ).

maintain the convection. Comparing the other cases, we can find that WS3-WAF2 forms small squall line and WS3-WS3 forms skewed front structure. WS5-WS3 seems to succeed in simulating squall line with organized structure, but the feature involves much unphysical effect as seen in the large negative water substances in the Figure 3 and Figure 4.

To clarify the cause of unsustainable squall line in the ENO3-ENO3, simulated squall line's structures are analyzed. Non-oscillatory scheme's characteristics are known to be robust even in the situation where the numerical oscillation usually occurs. However, on the other hand, the scheme has demerits due to the non-oscillatory characteristics, namely the scheme is numerically diffusive. This demerit of the scheme is considered to vanish the small structure of the squall line.

Figure 6 shows the instantaneous horizontal distributions of three-dimensional squall line experiments at 7 hours. It is found that front of the squall line consists of very small convergence area, where vertical wind speed appears and water vapor is condensed. This convergence area is originated and formed by the initial forcing which is given for the first 20 minutes simulation time. Further investigation on this convergence area revealed that non-oscillatory scheme cannot simulate water vapor condensation at the convergence area (Baba *et al.* 2010b). The results indicate that non-oscillatory scheme should not be applied as horizontal advection, and other scheme such as moderate high-order upwind scheme is more appropriate even though the scheme causes negative water substances.

## 5. Conclusions

Based on the study of Redelsperger *et al.* (2000), two- and three-dimensional squall line experiments are performed using various kinds tracer advection schemes, in order to investigate response of deep convection structure to the

applied tracer advection schemes.

Vertical characteristics with the advection schemes are first analyzed in the two-dimensional cases. It is found that finite difference and high-order upwind schemes tend to overestimate vertical convection by causing overshoot in computing the tracer advection. On the other hand, non-oscillatory scheme well suppresses the overshoot, and is found to be valid as vertical advection scheme.

In the three-dimensional cases, it is found that negative water substances are not so much affected by the different vertical advection schemes, except for the horizontal high-order upwind scheme which slightly overestimates vertical convection. When the non-oscillatory scheme is applied as a horizontal advection scheme, cumulus deep convection cannot be simulated. The cause of this fact is investigated by analyzing horizontal structures of the squall line. Front line of the squall line consists of small convergence area, where moisture is converted into the cloud water, and the cause of the failure is considered to be derived from the fact that the non-oscillatory scheme cannot capture this convergence area due to the scheme's characteristics, namely numerically diffusive.

In conclusion, the combination scheme which consists of the horizontal upwind and vertical non-oscillatory scheme can be the best tracer advection scheme for simulating deep convection.

### References

- Baba, Y., Takahashi, K., Sugimura, T., Goto, K., Dynamical core of an atmospheric general circulation model on a Yin-Yang grid, *Mon. Wea. Rev.*, Vol.138 (2010), pp.3988-4005.
- Baba, Y., Takahashi, K., Goto, K., Response of squall-line to tracer advection scheme, *J. Meteorol. Soc. Jpn.*, (2010), submitted.
- Grabowski, W. W., Toward cloud resolving modeling of large-scale tropical circulations: A simple cloud microphysics parameterization, *J. Atmos. Sci.*, Vol.55 (1998), pp.3283-3298.
- Li, X., Chen, D., Peng, X., Takahashi, K., Xiao, F., A multi-moment finite volume shallow water model on Yin-Yang overset spherical grid, *Mon. Wea. Rev.*, Vol.136 (2008), pp. 3066-3086.
- Peng, X., Xiao, F., Yabe, T., Tani, T., Implementation of the CIP as the advection solver in the MM5, *Mon. Wea. Rev.*, Vol.131 (2003), pp.1256-1271.
- Peng, X., Xiao, F., Ohfuchi, W., Fuchigami, H., Conservative semi-Lagrangian transport on a sphere and the impact on vapor advection in an atmospheric general circulation model, *Mon. Wea. Rev.*, Vol.133 (2005), pp.504-520.
- Redelsperger, J.-L., Brown, P. R. A., Guichard, F., Hoff, C., Kawasima, M., Lang, S., Montmerle, T., Nakamura, K., Saito, K., Seman, C., Tao, W. K., Donner, L. J., A GCSS model intercomparison for a tropical squall line observed during TOGA-COARE. I: Cloud-resolving models, *Q. J. R. Meteorol. Soc.*, Vol.126 (2000), pp.823-863.
- Satoh, M., Conservative scheme for a compressible nonhydrostatic model with moist processes, *Mon. Wea. Rev.*, Vol.131 (2003), pp.1033-1050.
- Schroeder, G., Schlunzen, K. H., Schimmel, F., Use of (weighted) essentially non-

- oscillatory advection schemes in a mesoscale model, *Q. J. R. Meteorol. Soc.*, Vol.132 (2006), pp.1509-1526.
- Shu, C.-W., Osher, S., Efficient implementation of essentially non-oscillatory shock-capturing schemes, II, *J. Comput. Phys.*, Vol.83 (1989), pp.32-78.
- Tomita, H., New microphysical schemes with five and six categories by diagnostic generation of cloud ice, *J. Meteorol. Soc. Jpn.*, Vol.86A (2008), pp.121-142.
- Toro, E. F., A weighted average flux method for hyperbolic conservation law, *Proc. Royal Soc. London*, Vol.A423 (1989), pp.401-418.
- Wicker, L. J., Skamarock, W.C., Time-splitting methods for elastic models using forward time schemes, *Mon. Wea. Rev.*, Vol.130 (2002), pp.2088-2097.