Reply to A. Kerkweg, Executive editor

General comment:

Dear authors,
In my role as Executive editor of GMD, I would like to bring to your attention our Editorial:
http://www.geoscientific-model-development.net/gmd_journal_white_paper.pdf
http://www.geosci-model-dev.net/6/1233/2013/gmd-6-1233-2013.html
This highlights some requirements of papers published in GMD, which is also available on the GMD website in the 'Manuscript Types' section:
In particular, please note that for your paper, the following requirements have not been met in the Discussions paper – please correct this in your revised submission to GMD.

: We are grateful to the executive editor for a careful reading of the manuscript. We revised all issues raised by the editor and revised the manuscript accordingly.

Comments:

(1) "– All papers must include a model name and version number (or other unique identifier) in the title."

: Thank you for the comments. The previous title "A semi-Lagrangian advection scheme for radioactive tracers in a regional spectral model" is changed to "A semi-Lagrangian advection scheme for radioactive tracers in the NCEP regional spectral model (RSM)".

(2) "– The paper must be accompanied by the code, or means of accessing the code, for the purpose of peer-review. If the code is normally distributed in a way which could compromise the anonymity of the referees, then the code must be made available to the editor. The referee/editor is not required to review the code in any way, but they may do so if they so wish.

: Thank you for the reviewer's comments. The code can be downloaded via the ECPC CVS server. We added "code availability" section at the end of the paper as follow:

"Code availability

One can access to the IsoRSM code through the concurrent versions system (CVS) server at the Center for Ocean-Atmospheric Preciction Studies (COAPS). Detailed descriptions how to get the code and install the model are located at the G-RSM homepage (http://g-rsm.wikispaces.com/Installation). For further information or requests on the model, please contact to E.-C. Chang (echang@kongju.ac.kr) or K. Yoshimura (kei@aori.u-tokyo.ac.jp).”

(3) “– All papers must include a section at the end of the paper entitled "Code availability". In this section, instructions for obtaining the code (e.g. from a supplement, or from a website) should be included; alternatively, contact information should be given where the code can be obtained on request, or the reasons why the code is not available should be clearly stated."

: As the reply to the comment #2, we added the code availability section.

Reply to Referee #1

General comment:

This article investigated implementation of semi-Lagrangian advection scheme in a specific type of numerical atmospheric model for limited-area, namely the Regional Spectral Model. It is mathematically known that usage of spectral dynamics can show up negative values when some features have spatially discontinuous distribution: known as Gibbs phenomenon. Since tracers and hydrometeors are definitely impossible to have negative value in the nature, the phenomenon causes serious errors especially when there is a single point emission of tracers.
The authors implemented semi-Lagrangian scheme to avoid the Gibbs phenomenon and evaluated behavior of simulated radioactive tracers with new advection scheme in their model, throughout a case of Japanese nuclear power plant explosion when it was hit by earthquake-induced tsunami. Effect of new advection scheme is very clear: noise-like signals formerly induced by Gibbs phenomenon are completely eliminated for tracers as well as hydrometeors.
The uniqueness of this study lies in their model framework and target of simulation; this advection scheme has rarely introduced in regional spectral model so far especially with considering emission of radioactive tracers. The objective of this study is very clear and it accomplished the authors' purpose appropriately. The paper is well-prepared and worth to be published. This reviewer raises few suggestions as below.

: We appreciate the reviewer who gave very constructive comments which significantly improved the earlier version of manuscript. We address all issues raised from the reviewer and the manuscript has been revised accordingly.

Specific comments:

[1] Besides elimination of Gibbs phenomenon for nonnegative variables, can the model bring additional improvements, such as enhanced performance and/or predictability? It is questionable at this stage; this reviewer recommends providing more and clarifying explanations in the manuscript.

: We are grateful to this anonymous reviewer for a valuable comment. As the reviewer's comment, one may expect model performance improvement by eliminating the Gibbs phenomenon. In the manuscript, we presented that the NDSL scheme can remove negative errors in radioactive variable fields and humidity field (Figs. 6-8). To show improvement in precipitation field, we added the TMPA rainfall in Fig. 9. Spatial correlation between the ORG (SL) and the TMPA is 0.616 (0.622).

It shows that error correction in humidity field can lead improvement in precipitation even the enhancement is not that much large. Because the selected case in this study is not a heavy rainfall case, it is quite hard to find the simulated rainfall improvement due to the corrected humidity. We added more explanation on this issue in section 4.3 as follow:

"General rainfall patterns observed in the tropical rainfall measuring mission (TRMM) multi-satellite precipitation analysis (TMPA) are well captured in both experiments (Fig. 9c). The spatial correlation coefficient of precipitation between the ORG run and the TMPA is 0.616 whereas the correlation coefficient between the SL run and the TMPA is 0.622. It means that the corrected humidity field by the NDSL scheme can slightly improve precipitation or keep the simulation skill of the original IsoRSM in the rainfall simulation. When we consider that the ORG experimental set have been widely used for various downscaling researches, it is possible to understand that the regional NDSL can successfully calculate the transport and distribution of humidity in the RSM. One possible reason why the improvement of the rainfall simulation by the NDSL scheme is not much significant is that the selected case in this study is not a heavy rainfall case. For a heavy rainfall case, the large discontinuity of humidity field is expected, which means higher possibility of negative value occurrences in the original IsoRSM. Further study will be continued to examine how the NDSL can improve skills for the precipitation simulation in a heavy rainfall cases."

To give direct answer to the reviewer, we would like to introduce the ORG and the SL runs with 50-km resolution for a heavy rainfall case occurred in 14-16 July 2001 over the mid-part of the Korean peninsular. Figure A1 shows 48-hours accumulated precipitation from the ORG run, the SL run, and the TMPA. It is clearly showed that the semi-Lagrangian advection scheme can improve an intense rainfall band. Please note that these results are not included in this paper because these experiments also examine impacts of a mass-conserving NDSL scheme (Zhang and Juang, 2012) for real-cases.

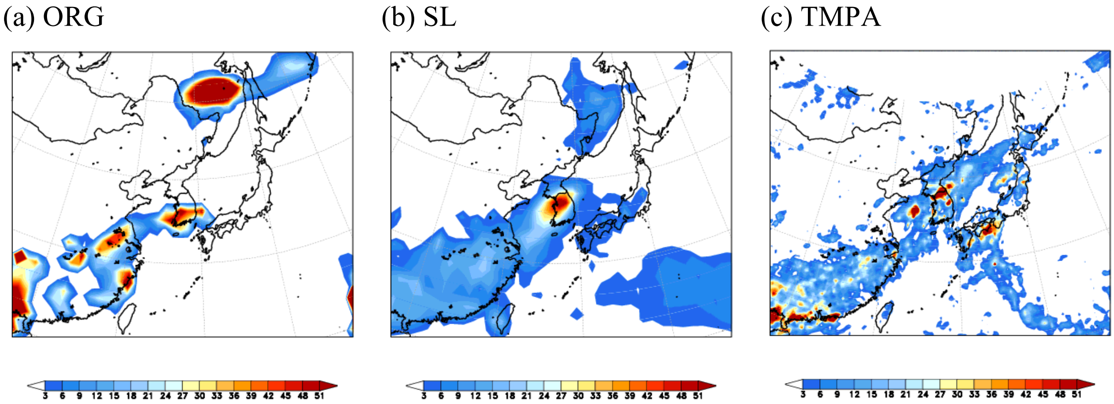

Fig. A1. 48-hours accumulated rainfall from (a) ORG run, (b) SL run, and (c) TMPA.

[2] Page 4222, in the first paragraph of the introduction, the authors may need to emphasize what the specific advantage of "regional" spectral model is.

: Responding to the reviewer's comment, we provide advantages of the regional spectral model in the introduction as follow:

"The RSM has advantages in accuracy for a regional high-resolution domain. In addition, the spectral representation of the RSM is two-dimensional perturbation method, which can eliminate the error due to reevaluation of the linear forcing from the base fields by the regional model (Juang et al., 1997). This is one of the reasons that the RSM can be easily used for long-range climate simulations."

[3] This reviewer recommends strengthening information given by the introduction section. Study of Staniforth and Côté (1991) provides classical and comprehensive review, which may be referable in this paper. Recently, some studies have endeavored semi-Lagrangian advection scheme in regional model frameworks (e.g., Aranami et al. 2014); referring and comparison with those studies may helpful to address uniqueness of this study.

: As the reviewer's recommendation, general review of the semi-Lagrangian and applying semi-Lagrangian method for a regional model are added in the introduction section.

"Staniforth and Côté (1991) reviewed semi-Lagrangian literatures for atmospheric models. They concluded that the semi-Lagrangian framework facilitates the incorporation of shape-preserving and monotonic schemes for moisture advection, because of the relatively small dispersion errors in the presence of discontinuities or near discontinuities."

"For regional model system, the flux through the boundaries is needed to apply the mass restoration, whereas there are no boundaries for global domains. Aranami et al. (2015) applied a mass restoration scheme for limited-area models (LAMs) with semi-Lagrangian advection. As such, the boundary treatment is required to apply the NDSL advection scheme for the RSM."

[4] Page 4223, line 3 to 4, it would be helpful if the authors provides brief descriptions about what kinds of topics have investigated with usage of regional spectral models. Besides NCEP RSM, there are series of regional spectral models that have been used (e.g., Lee and Hong 2014 and some references therein), which would be helpful to strengthen the importance of this study.

: We added more descriptions about previous studies as follow:

"Kang and Hong (2008) assessed impact of the land surface parameters on the regional climate circulations. Kanamitsu et al. (2010) presented a refined spectral nudging technique for regional dynamical downscaling. Chang and Hong (2011) used the RSM to produce regional future scenarios by dynamical downscaling. Li et al. (2012) showed that the fully coupled RSM and regional ocean modeling system (ROMS) can produce detailed oceanic circulations over the California coast."

We also considered including studies from different regional spectral models, such as GRIMs RMP (Lee and Hong, 2014). However, we think presenting researches by the NCEP RSM only is more efficient to emphasize advantages of the NDSL in the RSM.

[5] Page 4231, line 21, "However, ~ errors." Regarding to aforementioned description, it is hard to find materials underpinning this. Even though the simulated precipitation is far from the observation, as noted by the authors at the last paragraph of the last section, this reviewer thinks it is worth to show corresponding observation with respect to figure 9 and provide statistical index such as spatial correlation and/or root-mean- square error. This would be helpful to objectively explain even when model results are similar between ORG and SL experiments.

: Thank you for the reviewer's comment. As we replied to the comment #1, we included rainfall observation (TMPA) in Fig. 9 and presented spatial correlation coefficients for the ORG and the SL runs.

We modified that paragraph as follow:

"However, the simulated surface depositions of radioactive tracers are still deviate from the observation and precipitation from the SL experiment does not show significant improvement, even though the NDSL removes severe errors."

Technical corrections:

[1] Page 4224, line 1 to 2, GMP looks like different model to GRIMs while the GMP is a part of GRIMs. Please clarify the sentence.

: Corrected accordingly.

"the Global/Regional Integrated Model System (GRIMs; Hong et al., 2013) Global Model Program (GMP)."

Reply to Referee #2

General comments:

The manuscript describes the integration of a semi-Lagrangian transport scheme for mainly radioactive tracers into the National Centers for Environmental Prediction (NCEP) regional spectral model (RSM). In general, the manuscript is clearly understood with the well-chosen methodology. The semi-Lagrangian method improves the model's capability of maintaining positivity for certain tracers, which become negative due to numerical artifacts in the spectral expansion. While the paper appears to be a reasonably complete attempt and the effort is useful, the findings of the paper are not overly innovative. Semi-Lagrangian methods have been studied for a long time and their usage for tracer transport is also a well-documented idea. However, there are a few new ideas with respect to limited-area model. More detailed comments and recommendations are given below.

: We appreciate the reviewer for careful reading of the earlier version of the manuscript and providing valuable comments. We have tried to answer all issues raised by the reviewer and revise the manuscript accordingly based on the reviewer's comments.

Specific comments:

1. 1D and 2D idealized tests shown in this manuscript (Figs. 3 and 4) have been already completed satisfactorily by the previous studies (Juang 2007, 2008; Zhang and Juang 2012). Therefore, they seem to be not essential for this paper. I believe, however, that 3D idealized test is a prerequisite to real-case experiments in the presence of orography. When grid-spacing is not equal in the vertical (I guess this goes for your model), mass conservation of passive tracers should be more complicated question if dry air is not treated by SL scheme. In Fig. 7, vertical advection seems to be weakened by the SL in comparison with the ORG, which might be related to the aforementioned issue.

: Thank you for the reviewer's comment. As the reviewer commented, idealized tests are done by previous studies. What we would like to show is that the NDSL modified codes for the real-case in a regional model can transport disturbances correctly.

For vertical transport issue, figure B1 shows vertical velocity at the same time and space to the fig. 7. It is shown that the vertical motion from the SL is not weak than vertical motion of the ORG. In Fig. 7, large concentration parts of tracers from both experiments are not much different. Differences between two experiments in Fig. 7 are in light concentration area. It can be the result by the excessively strong diffusion in the ORG experiment, which is prescribed to reduce noises from the Gibbs phenomenon. These results supports that the NDSL advection of this study works properly in vertical direction for real-case configuration (i.e., non-uniform vertical grid spacing).

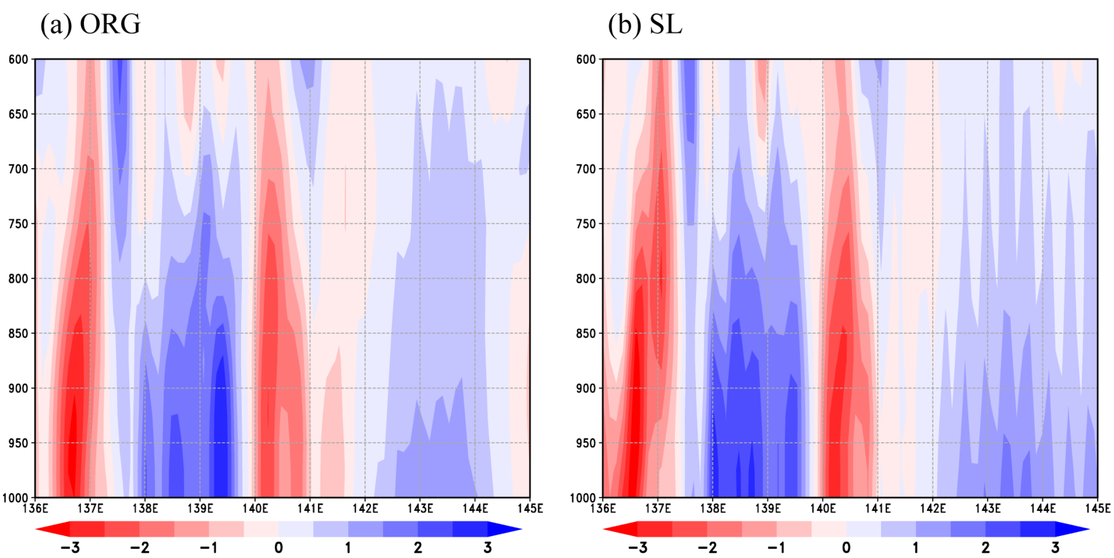

Fig. B1. Pressure vertical velocity (Pa s^{-1}) from (a) ORG run and (b) SL run averaged over 36.5°N-37.5°N at 12 UTC 15 March 2011.

2. Aside from the Gibbs-related issue, I wonder how the model performance is different between the ORG and SL simulations in terms of accuracy and efficiency. In this manuscript, the analysis is overall qualitative. There are no quantitative metrics to evaluate the model performance against the observed or analyzed data in case of real-case experiment, except for mass conservation in section 3. Even though the purpose of this study is not a "beauty contest" as the author stated in the final *section, it is undesirable that model performance is degraded just by applying a new advection scheme. Enhancement of physical parameterization should not be a fundamental solution to correct the error of dynamic-advection scheme.*

: We totally agree to the reviewer's comment. We added TMPA precipitation in Fig. 9 for quantitative evaluation. In the revised manuscript, following sentences are added in section 4.3.

"General rainfall patterns observed in the tropical rainfall measuring mission (TRMM) multi-satellite precipitation analysis (TMPA) are well captured in both experiments (Fig. 9c). The spatial correlation coefficient of precipitation between the ORG run and the TMPA is 0.616 whereas the correlation coefficient between the SL run and the TMPA is 0.622. It means that the corrected humidity field by the NDSL scheme can slightly improve precipitation or keep the simulation skill of the original IsoRSM in the rainfall simulation. When we consider that the ORG experimental set have been widely used for various downscaling researches, it is possible to understand that the regional NDSL can successfully calculate the transport and distribution of humidity in the RSM. One possible reason why the improvement of the rainfall simulation by the NDSL scheme is not much significant is that the selected case in this study is not a heavy rainfall case. For a heavy rainfall case, the large discontinuity of humidity field is expected, which means higher possibility of negative value occurrences in the original IsoRSM. Further study will be continued to examine how the NDSL can improve skills for the precipitation simulation in a heavy rainfall cases."

3. There is a lack of detailed description in model and experimental design. For example, what is the perturbation method, global model program (GMP), initial and lateral boundary conditions? How did you treat negative values which are inherent in the initial fields or might be generated by physical parameterizations?

: For perturbation method, we added follow:

"The RSM has advantages in accuracy for a regional high-resolution domain. In addition, the spectral representation of the RSM is two-dimensional perturbation method, which can eliminate the error due to reevaluation of the linear forcing from the base fields by the regional model (Juang et al., 1997). This is one of the reasons that the RSM can be easily used for long-range climate simulations."

For GMP, we revised the description as "the Global/Regional Integrated Model System (GRIMs; Hong et al., 2013) Global Model Program (GMP)."

For initial and boundary condition, we added follow:
"Atmospheric initial and lateral boundary conditions are provided by the NCEP-Department of Energy (DOE) reanalysis (Kanamitsu et al., 2002)."

For negative values in initial field and after physics processes, we added follow in section 4.1:
"In the case that negative values are introduced in the initial field, correction is performed in regional interpolation process by replacing negative values with zero. If negative tracer quantities are produced by the physical parameterizations, those negative values are transported to above layer and original values are replaced by zero."

4. Newly-developed boundary treatment is not sufficiently evaluated on condition that tracers flow in and out at the boundary. Would it be difficult to include the SL simulation with a source near the boundary?

: Evaluation of the boundary treatment for applying semi-Lagrangian method in regional model is essential part as the reviewer commented. However, there is one assumption for boundary treatment in this study. That is no wind advection in the "boundary zone" of Fig. 2. Because when we allow transport by the wind in the "boundary zone", advected disturbances from the semi-Lagrangian may have different location to the disturbances provided by the lateral boundary condition. In the "boundary zone", entirely boundary information is used. It also means that the advection in the "boundary zone" is totally acquired from the lateral boundary condition. Thus, it is conceptually impossible to check the advection when the source is located in "boundary zone". Presented ideal tests in the manuscript assumed that the initial disturbance is located in the "inner domain".

On the other hand, in the real-case run, the SL run simulated almost similar humidity and precipitation distributions with the ORG experiment for 16-days integration, which can be evidence that the boundary treatment of this study works normally.

5. P4225L8 "(1) non-iteration to find the departure and arrival points of each tracers;" In general, semi-Lagrangian approach does not require iteration for departure and arrival points but for trajectory in some cases, so this is not unique feature of the NDSL scheme.

: We are extremely grateful to the reviewer's precise comment. We revised the sentence as "1) non-iteration to compute the trajectories of each tracer;".

6. P4225L13-15 "In this case, . . . to the arrival point." This is not correct: It requires solving the ODE for trajectories, which is often accomplished by a simple fixed point iteration. It could also be done by applying other ODE solvers.

: Thank you for the comment. We carefully reviewed the NDSL literatures and revised the sentence as follow:
"In this case, an initial guess and iterations to compute the trajectories are required, which means finding mid-point wind and transferring the fluid particles from the departure points to the arrival points."

7. P4225L21 ". . .the scheme is computationally efficient." Contrary to the authors' claim, the trajectory calculations are relatively cheap. Usually only two iterations suffice and communications for parallel codes are not necessary. Remapping is substantially more expensive for both serial and parallel codes. Remapping needs reconstruction, monotone and positive filters, and integration. It also needs communications across adjacent processors to maintain exact mass conservation. Therefore, it is clear that replacing a scheme with 1 trajectory + 1 remapping (two-time-level) with 2 remappings (three-time-level NDSL) is certainly less efficient. Furthermore, NDSL uses dimensional splitting and performs a series of one-dimensional remappings. To remove the bias on the order in which the remapping is *done for higher dimensions, NDSL uses an average of several remappings with permutation of the order of remapping. Therefore, looking at the details of the scheme, it is inconceivable to reach the conclusion that NDSL is more computationally efficient than other schemes in the literature.*

: We believe this comment is essential for our research to deliver correct information. We understand what the reviewer is explaining. The expression is removed in the revised manuscript.

8. It seems to me that Figures 6c-6d and 7c-7d are not meaningful because there are no significant differences from Figures 6a-6b and 7a-7d.

: As the reviewer's comment, we only retained simulated cesium-137 in Figs. 6 and 7.

Reply to Referee #3

Major comments:

Overall the manuscript is clear and the subject is much interesting to the readers of the GMD. I have a couple of questions and suggestions.

: We grateful to this reviewer for careful reading of the manuscript and providing valuable and detailed comments. We tried to revise the article carefully as the reviewer's commented.

1. Computational burden: With the NDSL, is there any extra computational burden? In either case, it's better be described and discussed in the manuscript.

: Thank you for the reviewer's comment. We also considered describing this issue in the manuscript. The current NDSL scheme in the RSM brings approximately 35% increased computational cost with respect to the original version. However, there still exist the spectral advection calculation in the RSM with the NDSL even the spectral advection result is not used any more. Thus, it is hard to estimate the computational burden when the NDSL replaces the original spectral advection. Removing spectral calculation for tracers when the NDSL is used is the work to do before official release. We added follow in the revised manuscript.
"When the NDSL advection used (the SL experiment), there occurs extra computation cost of 35% with respect to the ORG run. However, the current version of the NDSL in the RSM still calculates spectral tracer advections even the result is not used any more. It means that the computational burden with the current NDSL in the IsoRSM is purely the increased computational cost which is required for the NDSL tracer advections. In updated release, this inefficiency will be solved."

2. What is the order of the accuracy in the NDSL?

: The NDSL uses three-time-level differential which has second-order of the accuracy in time. For spatial interpolation and remapping, the piecewise parabolic method is used in the NDSL which has third order accuracy.

3. boundary/buffer zones: What are the minimum numbers of the grid points for these two zones? It is not uncommon to have these in the regional model. In real case, 5 times delta_x is used. Is it the minimum recommended by the authors?

: When we tested the real-case experiment, the minimum grids for boundary and buffer zone was 2-grids for each direction. We recommended 5-grids for boundary and buffer zone with some stability. In our case, 10 km horizontal resolution and 40 sec time step interval are used. If these resolutions are changed, those boundary and buffer zone setup may be changed accordingly. The guide line will be provided in the manual.

4. For idealized experiment, can the authors provide the original advection scheme's error? Also, I'd be interesting to know if one uses a longer time step (2 x delta_t). However, it is not necessary to perform this extra experiment.

: Thank you for the reviewer's constructive recommendation. We made a simple advection driver for the NDSL scheme in this study. It's not much complicated to make the driver because tracers always exist on grid-spaces. To make the same driver for the original advection scheme, wave-grid spatial transform part should be included. It is absolutely possible to make the spectral driver for ideal test, but we could not make the driver in this review process. We will make the frame for idealized experiment as the reviewer commented.

For longer time step in ideal test, we checked 2dt and 3dt cases. Figure C1 shows x-directional advection test for the NDSL. Conditions are same as in the manuscript, but for x-direction only. It is shown that results from 3 different time steps are almost overlapped.

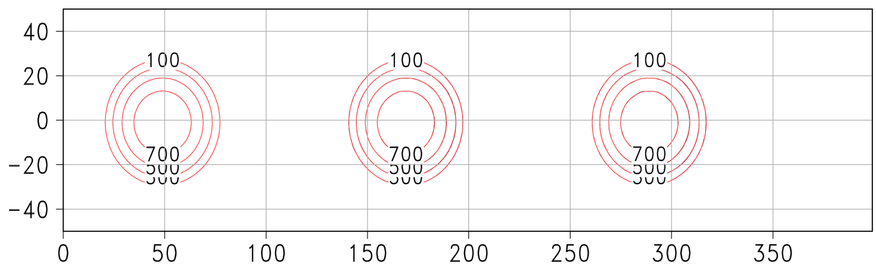

Fig. C1. Idealized x-directional advection with different time steps. Black, blue, and red contours indicate the results with Δt of 100s, 200s, and 300s.

5. I want to confirm that these tracers don't have sink terms as of the current implementation, right?

: In dynamical advection process for the NDSL, there is no sink terms. However, there are dry and wet deposition processes for radioactive tracers as described in section 2.1. These depositions are considered in physical process, and it works as a sink terms for tracers.

Finally, I'm wondering if the NDSL will be included in the official release of the RSM.

: The NDSL will be a part of officially distributed RSM.

A Semi-Lagrangian advection scheme for radioactive tracers in ~~a~~the NCEP regional spectral model (RSM)

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Abstract

In this study, the non-iteration dimensional-split semi-Lagrangian (NDSL) advection scheme is applied to the National Centers for Environmental Prediction (NCEP) regional spectral model (RSM) to alleviate the Gibbs phenomenon. The Gibbs phenomenon is a problem wherein negative values of positive-definite quantities (e.g., moisture and tracers) are generated by the spectral space transformation in a spectral model system. To solve this problem, the spectral prognostic specific humidity and radioactive tracer advection scheme is replaced by the NDSL advection scheme, which considers advection of tracers in a grid system without spectral space transformations. A regional version of the NDSL is developed in this study and is applied to the RSM. Idealized experiments show that the regional version of the NDSL is successful. The model runs for an actual case study suggest that the NDSL can successfully advect radioactive tracers (iodine-131 and cesium-137) without noise from the Gibbs phenomenon. The NDSL can also remove negative specific humidity values produced in spectral calculations without losing detailed features.

1 Introduction

The spectral method is a numerical method applied to primitive meteorological equations to achieve high-order accuracy (Robert, 1966). The spectral method has advantages over the finite difference method: the absence of truncation error in linear terms, the absence of aliasing and phase errors, the absence of pole problems in global models, and the efficient use and simple programming of semi-implicit time integration (Bourke, 1974). Applying the spectral method in a regional model can be difficult due to time-dependent lateral boundary conditions. However, several approaches for solving this problem have been successful (e.g., Tatsumi, 1986; Fulton and Schubert, 1987; Hoyer, 1987; Segami et al., 1989; Chen and Kuo, 1992). Juang and Kanamitsu (1994) presented the National Centers for Environmental Prediction (NCEP) regional spectral model (RSM~~), which uses ~~). The RSM has advantages in accuracy for a regional high-resolution domain. In addition, the spectral ~~representations and the ~~representation of the RSM is two-dimensional perturbation method~~.~~, which can eliminate the error due to reevaluation of the linear forcing from the base fields by the regional model (Juang et al., 1997). This is one of the reasons that the RSM can be easily used for long-range climate simulations. The RSM has been widely used for regional downscaling research (e.g., Kang and Hong, 2008; Kanamitsu et al., 2010; Chang and Hong, 2011; Li et al., 2012). Kang and Hong (2008) assessed impact of the land surface parameters on the regional climate circulations. Kanamitsu et al. (2010) presented a refined spectral nudging technique for regional dynamical downscaling. Chang and Hong (2011) used the RSM to produce regional future scenarios by dynamical downscaling. Li et al. (2012) showed that the fully coupled RSM and regional ocean modeling system (ROMS) can produce detailed oceanic circulations over the California coast.

Although the RSM has advantages, it also has a problem common in spectral model systems: the Gibbs phenomenon. This phenomenon is “overshooting” in the convergence of the partial sums of particular Fourier series in the neighborhood of a discontinuity of the function being expanded. In the case of spectral techniques, the Gibbs phenomenon can introduce negative values in positive-definite variables (i.e., hydrometeors and tracers). Yoshimura (2011) presented a tracer simulation for the Fukushima Dai-ichi nuclear power plant accident during the massive earthquakes and tsunami on 11 March 2011 in eastern Japan by utilizing the stable isotope mode of the RSM (IsoRSM; Yoshimura et al., 2010). General features, e.g., the tracers from Fukushima reached the metropolitan area and significant amounts of tracers were precipitated, are well captured in this simulation. However, these simulations also clearly show that computational noise is produced by the Gibbs phenomenon near the emission point. This problem is quite severe in this simulation because radioactive materials are emitted from a single grid-point source at the surface level, which creates a significant discontinuity in the wave space transformation. Thus, an advection method that does not require a spectral transformation for tracers is needed to resolve the Gibbs phenomenon.

The semi-Lagrangian method is an alternative advection scheme that can replace the spectral calculation of hydrometeors and tracers. Semi-Lagrangian advection schemes have long been preferred in numerical weather prediction because they are more accurate and efficient than traditional Eulerian schemes when large time steps are considered (Williamson, 2007). Staniforth and Côté (1991) reviewed semi-Lagrangian literatures for atmospheric models. They concluded that the semi-Lagrangian framework facilitates the incorporation of shape-preserving and monotonic schemes for moisture advection, because of the relatively small dispersion errors in the presence of discontinuities or near discontinuities. Juang (2007, 2008) proposed a non-iteration dimensional-split semi-Lagrangian (NDSL) scheme, which is simple and economical compared with the conventional semi-Lagrangian method. Although the NDSL scheme has not yet been applied to the regional spectral model, some versions of the NDSL have been added to the global spectral model system, e.g., NCEP Global Forecast System (GFS; Moorthi et al., 2001), the Global/Regional Integrated Model System (GRIMs; Hong et al., 2013), and the Global Model Program (GMP).) Global Model Program (GMP). For regional model system, the flux through the boundaries is needed to apply the mass restoration, whereas there are no boundaries for global domains. Aranami et al. (2015) applied a mass restoration scheme for limited-area models (LAMs) with semi-Lagrangian advection. As such, the boundary treatment is required to apply the NDSL advection scheme for the RSM.

The objective of this study is to remove the Gibbs phenomenon for hydrometeors and tracers in the regional spectral model by replacing the spectral tracer advection scheme with the semi-Lagrangian advection scheme in a real simulation. Detailed features of the semi-Lagrangian version of the regional spectral model and the experimental design are described in Section 2. Section 3 provides results from the original IsoRSM and the semi-Lagrangian version of IsoRSM for radioactive tracers and humidity fields in the Fukushima nuclear power plant accident case study. A summary and conclusion are provided in Section 4.

2 Method

2.1 Regional spectral model for radioactive tracers

Yoshimura et al. (2010) presented the IsoRSM, which includes the isotopic species for water vapor (HDO and $H_2^{18}O$) as tracers in the latest version of the Scripps Experimental Climate Prediction Center's regional spectral model (Kanamitsu et al., 2005). In the IsoRSM, the tracers can be incorporated into raindrops or cloud particles at every integration time step. Therefore, the interactions between the tracers and precipitation processes can be considered. In contrast, a general chemical transport model uses precipitation as an external forcing. Yoshimura (2011) and Saya et al. (2013) modified IsoRSM to enable the simulation of the transport of radioactive tracers. Isotopic variables were replaced with radioactive tracers (i.e., ^{131}I and ^{137}Cs), and dry and wet deposition processes caused by gravity and precipitation processes, respectively, were introduced. Saya et al. (2013) proposed a wet deposition process wherein the deposition is proportional to the ratio of the amount of condensed water to the total amount of water, whereas a traditional method (e.g., Maryon, 1991) considers only the amount of condensed water. In this study, the radioactive tracer mode of IsoRSM is used as an original framework.

2.2 NDSL scheme for RSM

In this study, the NDSL advection scheme replaces the spectral prognostic calculation of the tracers in the RSM. Once each tracer field is provided from the initial field on the regular grid space, the advection of these fields is calculated by the NDSL on the grid space without any spectral transformation during the model integration. This process prevents the Gibbs phenomenon. The NDSL has two characteristics: 1) non-iteration to ~~find~~compute the ~~departure and arrival points~~trajectories of each tracer; and 2) a dimensional-splitting method. Figure 1 shows the basic concept of two-dimensional advection for both the traditional semi-Lagrangian scheme and the NDSL scheme (from Juang 2008). The traditional backward (forward) semi-Lagrangian scheme assumes that the arrival (departure) points are located on the regular model grid (Fig. 1a). In this case, an initial guess and ~~iteration~~iterations to compute the trajectories are required~~ to find the ~~, which means finding mid-point ~~winds~~wind and ~~to transfer tracers~~transferring the fluid particles from the departure ~~point~~points to the arrival ~~point~~points. These iterations make the semi-Lagrangian scheme expensive and inefficient. The NDSL scheme is a central scheme, which assumes a mid-point wind at the regular model grid point at time t to find the departure point at time $t-\Delta t$ and the arrival point at time $t+\Delta t$ (Fig. 1b, also see Fig. 1 of Zhang and Juang, 2012). No initial guess or iteration is needed to find trajectories. Only one interpolation at the departure point and one remapping at the arrival point are needed~~; thus, the scheme is computationally efficient.~~. The wind in the central scheme can reduce numerical error better than the upstream scheme because no estimation or iteration occurs. During the advection process, the quantity of the tracer is assumed to be steady. The NDSL uses the dimensional-splitting method for 2D advection, which simply splits the 2D advection into a sequence of 1D advections. Because it only needs 1D interpolation and remapping, the method easily attains mass conservation. Another important advantage is that the 1D method can be easily coded; thus, it is compatible with most numerical models.

For the implementation of the regional version of the NDSL in a real-data case, the boundary treatment must be considered. The global NDSL uses a cyclic boundary condition, which places a duplicated global domain at the western and eastern boundaries. This allows for the arrival or departure point to be located, even when it lies outside of the model domain. However, cyclic boundary conditions are not suitable for regional domains because the domain edge points differ in both longitude and latitude. Thus, the domain is treated as three sections: the boundary zone, the buffer zone, and inner domains. Figure 1 shows the structure of these sections in the lower-left corner of the model domain as an example; it assumes that the boundary and buffer zones are defined as three grid points each. The boundary zone (dark gray in Fig. 2a) is the area where the semi-Lagrangian advection calculation is not applied and where the values of the global base field are specified. This area is necessary to prevent the calculated departure point of tracers located outside of the model domain. The values in the inner domain are calculated entirely from the regional model. In the buffer zone (light gray in Fig. 2a), the global base field and the regional model field are combined, with the weighting determined by an inverse exponential function (Eq. 1 and Fig. 2b), to smooth the gap between the boundary zone and the inner domain.

$$W_G = \frac{1}{e^k} \qquad (1)$$
$$W_R = 1 - W_G$$

Here, W_G is the weighting for the global base field, W_R is the weighting for the regional model field, and k is the grid point of the buffer zone toward the inner domain. W_G is defined according to Eq. 1 in the buffer zone but is specified as 1 and 0 in the boundary zone and the inner domain, respectively. Finally, the result over the model domain is defined by Eq. 2:

$$F = W_G F_G + W_R F_R \qquad (2)$$

where F is the final result of a particular tracer, F_G is the global base field, and F_R is the field calculated by the regional model.

3 Idealized experiment

An idealized experiment is performed to examine the feasibility of the regional version of the NDSL advection scheme. A horizontal advection scheme is examined in the 2D domain, which has 400 east-west grid points and 400 north-south grid points, with a 10-km resolution. A uniform wind field of 10 m s^{-1} in both the x and y directions is used for horizontal advection. The integration time interval (Δt) is set to 10 seconds. Figure 3a shows the result of this horizontal advection every 1000 time steps. An ideal perturbation is imposed at the initial step, and the shape of the perturbation is maintained during the integration up to the 3000th time step. The transported disturbance by the NDSL scheme at the 3000th time step is compared to the analytic solution (Fig. 3b); these two results are nearly identical. The shaded values in Fig. 3b indicate differences between the analytic solution and the result calculated from the NDSL. The differences are less than 1% of the maximum disturbance. The ratio of the mass change due to the NDSL to the initial mass (Eq. 3) is verified to confirm that the NDSL satisfies mass conservation.

$$R_{mass} = \frac{(total\ mass) - (initial\ total\ mass)}{(initial\ total\ mass)} \qquad (3)$$

$R_{mass} \approx 10^{-15}$ up to the 3000th time step, which shows that the NDSL scheme satisfies mass conservation during the integration.

The idealized vertical advection experiment is performed in one dimension. The vertical dimension is the sigma coordinate, which has 100 layers from 1 (bottom) to 0 (top) with equal spacing (0.01). A uniform vertical velocity of 10^{-4} sigma s^{-1} is prescribed. The integration time interval (t) is 100 seconds. Figure 4 shows that the virtual concentration at the initial time is conserved during the transport process. The mass conservation ratio for vertical advection is R_{mass} 10^{15}.

The idealized experiments in the horizontal and vertical directions verify that the regional version of the NDSL scheme can accurately calculate the advection of these specific perturbations in the horizontal and vertical directions while conserving mass.

4 Real-case experiments

4.1 Experiment design

For the Fukushima case study, two experiments are performed. The first is the ORG run, which is identical to the control experiment of Saya et al. (2013), wherein tracer fields are calculated in the spectral space, as is performed in the original IsoRSM. The second is the SL run, wherein the specific humidity and radioactive material (^{131}I and ^{137}Cs) tracer fields are calculated by the NDSL scheme. All configurations except the advection method for tracers are identical in the two experiments. Figure 5 shows the experimental domain for the case study, with horizontal grid spacing of 10 km. The number of grid points is 161 (east-west) by 200 (north-south). The number of vertical layers is 28 in terrain-following sigma coordinates; the lowest and highest sigma levels are 0.995 and 0.002, respectively. The red circle in Fig. 5 indicates the emission point, which is the location of the Fukushima Dai-ichi nuclear power plant. The physical processes used are the relaxed Arakawa-Schubert deep convection scheme (Moorthi and Suarez, 1992), the Noah land surface model (Ek et al., 2003), the Chou radiation scheme (Chou and Suarez, 1994), and a non-local planetary boundary scheme (Hong and Pan, 1996). The model simulation is integrated from 00 UTC 12 March 2011 to 00 UTC 28 March 2011 (16 days). Atmospheric initial and lateral boundary conditions are provided by the NCEP-Department of Energy (DOE) reanalysis (Kanamitsu et al., 2002). In the case that negative values are introduced in the initial field, correction is performed in regional interpolation process by replacing negtive values with zero. If negative tracer quantities are produced by the physical parameterizations, those negative values are transported to above layer and original values are replaced by zero. The emission rate of the radioactive tracers from Chino et al. (2011) is used in this study. To determine the size of the boundary and buffer zones (Fig. 2) for this case study, the fastest wave is assumed to be a sound wave, which moves at a speed of 300 m s^{-1}. The estimated longest traveling distance of this wave in one time step (t=40 sec) is 12 km; this value is less than 2 x. Therefore, the fastest-moving tracer is confined within 2 grid points over one time step. Thus, it is impossible for tracers to enter from outside the domain when the boundary zone is larger than 2 x. In this study, the boundary zone is set to 5 x for safety. The buffer zone is the same size as the boundary zone.

When the NDSL advection used (the SL experiment), there occurs extra computation cost of 35% with respect to the ORG run. However, the current version of the NDSL in the RSM still calculates spectral tracer advections even the result is not used any more. It means that the computational burden with the current NDSL in the IsoRSM is purely the increased computational cost which is required for the NDSL tracer advections. In updated release, this inefficiency will be solved.

4.2 Radioactive tracer field

Figure 6 shows column-integrated atmospheric radioactive tracerstracer (^{137}Cs) from the ORG and the SL experiments at 12 UTC 15 March 2011, when the maximum emission rates occurred. The ORG run produces very distinct noise in the zonal and meridional directions from the emission point; these values are shown in both the ^{131}I and ^{137}Cs tracers (Figs. 6a and 6c). (Fig. 6a). Additionally, a ring-shaped signal surrounds the emission point. This signal is the pattern of high-concentration, empty values; the ring shape extends from the center of the emission to outside the domain. These signals, also known as the ringing artifact, are typical of the Gibbs phenomenon. In the Fukushima case study, the discontinuity of the tracer field is pronounced because the tracers are emitted from a single grid point, which leads to significant noise from the spectral transformation processes in the ORG experiment. Widespread distributions of tracers with small concentrations occur over the domain. However, the SL experiment does not have any noise from the Gibbs phenomenon (FigsFig.

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6b and 6d). Compared with the ORG run, the SL experiment produces a generally similar pattern of tracers, which advect northeast from the emission point. This result is the clearest advantage of the semi-Lagrangian advection scheme for tracer transport in the spectral model system. The simulated ^{131}I tracers have almost same patterns with the ^{137}Cs in both the ORG and the SL runs (figure not shown). Figure 7 shows longitudinal-vertical cross sections of tracers averaged in the meridional direction over 36.5°-37.5°N, which includes the emission point. This figure shows that the ringing noises extend above the surface in the ORG experiment (Figs. 7a and 7c). The SL experiment shows transport in the vertical and horizontal directions without computational noise. Clearly, the semi-Lagrangian advection method can calculate the transport of tracers without computational noise, whereas the spectral representation of advection produces severe errors.

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4.3 Humidity field

The SL experiment applies the semi-Lagrangian method to radioactive tracers and the humidity field. The humidity field is also a positive-definite field and spectrally exhibits the Gibbs phenomenon, although the discontinuity is not as strong as it is in the radioactive tracer fields. Figure 8 shows that the specific humidity in the ORG run exhibits some negative values in the lower troposphere (Figs. 8a and 8b). The SL experiment simulates detailed humidity distributions that are similar to those of the ORG experiment but without any negative values (Figs. 8c and 8d). Negatives in the ORG run indicate that the original RSM has a systematic problem representing the positive-definite field, even though the RSM is widely used and evaluated for regional downscaling. The precipitation fields from each experiment are quite similar (Fig. 9). Because the precipitation is calculated from the humidity field and other atmospheric circulation fields, this result indicates that the regional NDSL can successfully calculate the transport and distribution of humidity in the RSM.The 16-days accumulated precipitation fields from each experiment are quite similar (Figs. 9a and 9b). General rainfall patterns observed in the tropical rainfall measuring mission (TRMM) multi-satellite precipitation analysis (TMPA; Huffman et al., 2007) are well captured in both experiments (Fig. 9c). The spatial correlation coefficient of precipitation between the ORG run and the TMPA is 0.616 whereas the correlation coefficient between the SL run and the TMPA is 0.622. It means that the corrected humidity field by the NDSL scheme can slightly improve precipitation or keep the simulation skill of the original IsoRSM in the rainfall simulation. When we consider that the ORG experimental set have been widely used for various downscaling researches, it is possible to understand that the regional NDSL can successfully calculate the transport and distribution of humidity in the RSM. One possible reason why the improvement of the rainfall simulation by the NDSL scheme is not much significant is that the selected case in this study is not a heavy rainfall case. For a heavy rainfall case, the large discontinuity of humidity field is expected, which means higher possibility of negative value occurrences in the original IsoRSM. Further study will be continued to examine how the NDSL can improve skills for the precipitation simulation in a heavy rainfall cases.

5 Summary and discussion

In previous studies, the RSM has been utilized to simulate the Fukushima Dai-ichi nuclear power plant accident. The results exhibit severe noise in the simulated radioactive tracer fields (i.e., iodine-131 and cesium-137). This noise is due to the Gibbs phenomenon, wherein discontinuities in positive-definite fields create negative values after spectral transformations. This problem is common in spectral model systems. The spectral tracer advection is replaced with a semi-Lagrangian advection scheme to prevent the Gibbs phenomenon in the tracer output. Prognostic tracer fields are calculated using the semi-Lagrangian method and are only considered in grid space. The Gibbs phenomenon does not occur when the spectral space transformation is not performed.

The semi-Lagrangian method used in this study is the NDSL scheme, which has the advantages of efficiency and simplicity. Because the NDSL has been previously applied in a global model system only, a regional version of the NDSL is developed in this study. For this application, the boundary conditions are applied by defining simple weighting functions. The regional version of the NDSL scheme is verified by performing idealized experiments using horizontal and vertical advection. These idealized experiments transport a particular disturbance to the uniform wind field. The results show that the shape is well maintained and the mass conservation is satisfied during advection. Therefore, the regional version of the NDSL is successfully applied in the RSM.

Two experiments are performed for the Fukushima case study to evaluate the NDSL advection scheme in the RSM. The ORG experiment is performed by the original RSM, and the SL experiment is produced by the NDSL version of the RSM. The ORG run shows severe errors in tracer fields induced by the Gibbs phenomenon. Errors appear as a ringing signal that extends zonally and meridionally from the emission point. Additionally, relatively strong ring-shaped noise is captured around the emission point. This noise is clearly removed when the tracer advection component is replaced by the NDSL scheme. The SL run shows that the NDSL advection scheme can capture the major transport of tracers without any noise from the Gibbs phenomenon. This finding is the clearest advantage of the NDSL scheme in the tracer field simulation. In the humidity field, the ORG experiment produces some negative values in the lower troposphere. However, the SL experiment does not exhibit such negatives; both SL and ORG capture the detailed distribution of the humidity field. The precipitation fields from the ORG and SL experiments are similar, which means that the NDSL properly calculates the humidity field.

This study reveals that replacing the tracer advection scheme with a semi-Lagrangian scheme can eliminate the Gibbs phenomenon in a regional spectral model. However, the simulated surface ~~deposition~~depositions of radioactive tracers are still deviate from the observation and precipitation from the SL experiment ~~still deviate from the observations~~does not show significant improvement, even though the NDSL removes severe errors. Note that the objective of this study is to determine the feasibility of the NDSL advection scheme in a regional spectral model. Thus, some quantitative validations from experiments are not included in this study. These results may be improved upon by applying enhanced physical parameterizations and advanced formulas for tracer surface deposition processes.

Code availability

One can access to the IsoRSM code through the concurrent versions system (CVS) server at the Center for Ocean-Atmospheric Preciction Studies (COAPS). Detailed descriptions how to get the code and install the model are located at the G-RSM homepage (http://g-rsm.wikispaces.com/Installation). For further information or requests on the model, please contact to E.-C. Chang (echang@kongju.ac.kr) or K. Yoshimura (kei@aori.u-tokyo.ac.jp).

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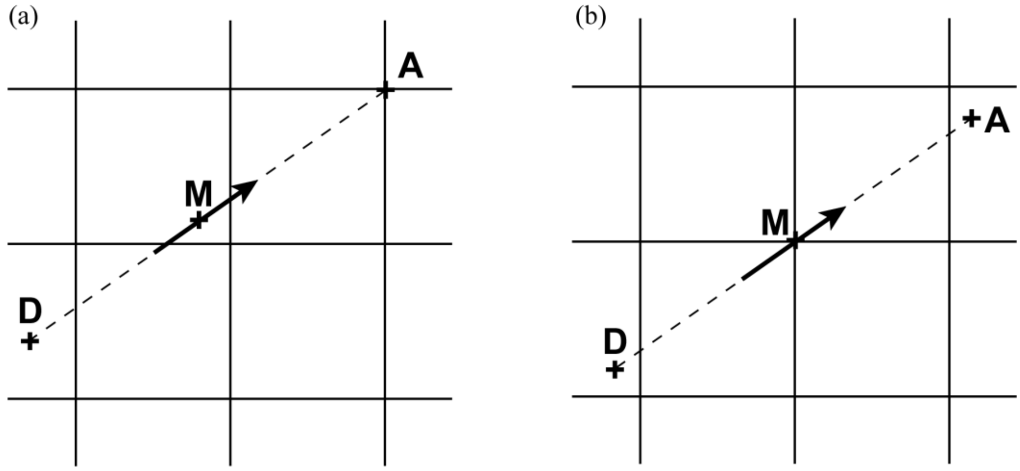


Figure 1. Schematic of two-dimensional advection for (a) the traditional backward semi-Lagrangian scheme and (b) the NDSL scheme. “D,” “M,” and “A” indicate the departure point, mid-point, and arrival point, respectively. The bold arrow indicates the wind vector at the mid-point.

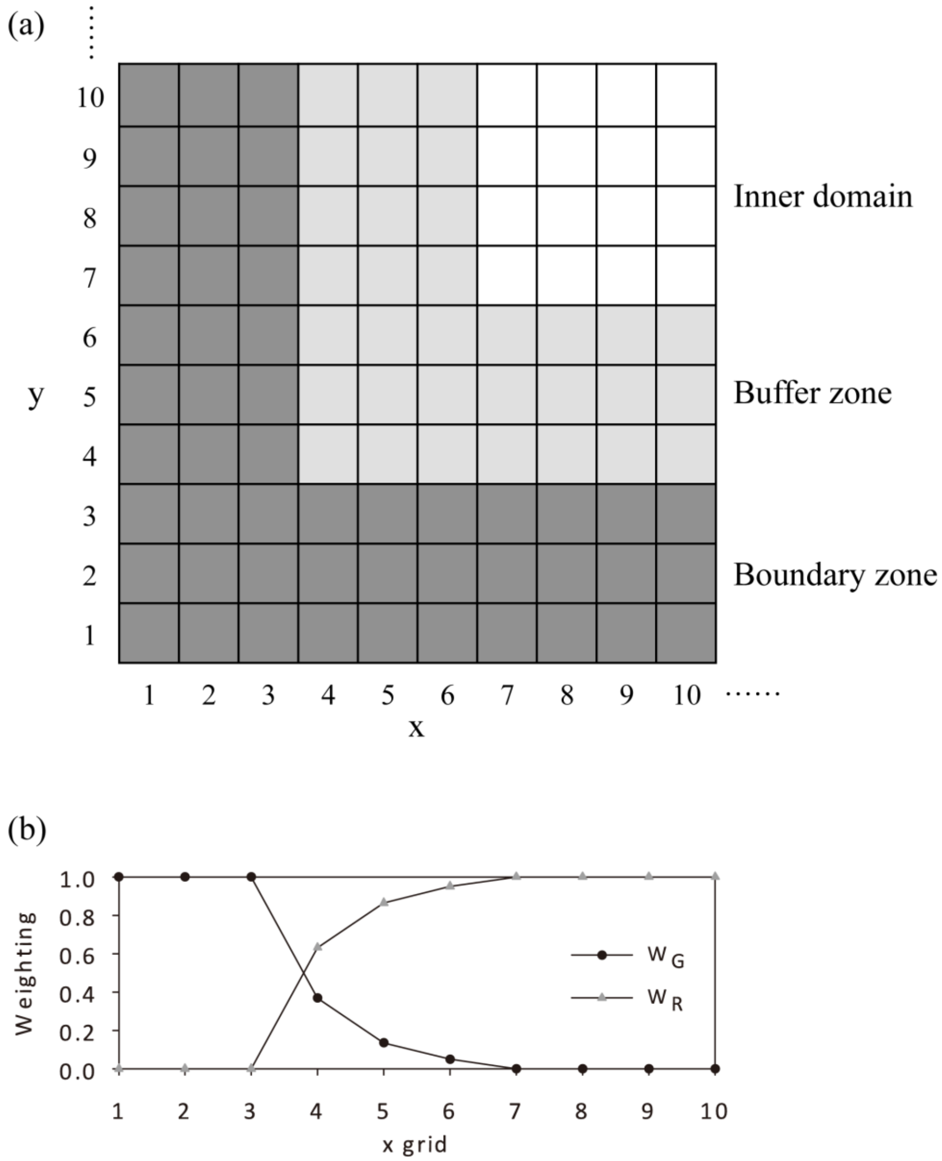


Figure 2. (a) The structure of the lower-left corner in the regional domain for boundary treatment. (b) Weighting function of the global base field (black) and regional model field (gray) along the x-axis, which includes the inner domain. This example assumes that the grid size of the boundary and buffer zones is 3.

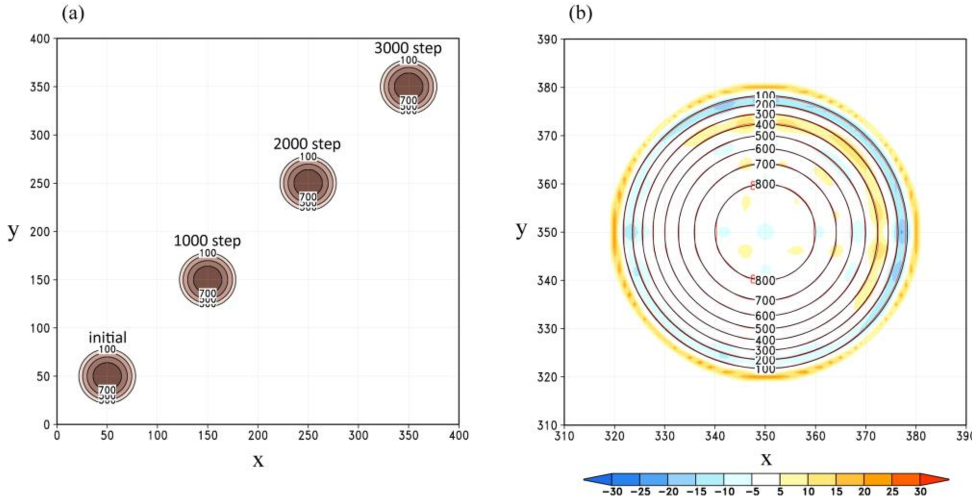


Figure 3. Result from the idealized horizontal advection experiment. (a) Virtual concentration every 1000 time steps by the NDSL advection scheme and (b) results at the 3000th time step from the NDSL (red contour) and the analytic solution (black contour). The shaded values indicate the differences between the NDSL results and the analytic solution.

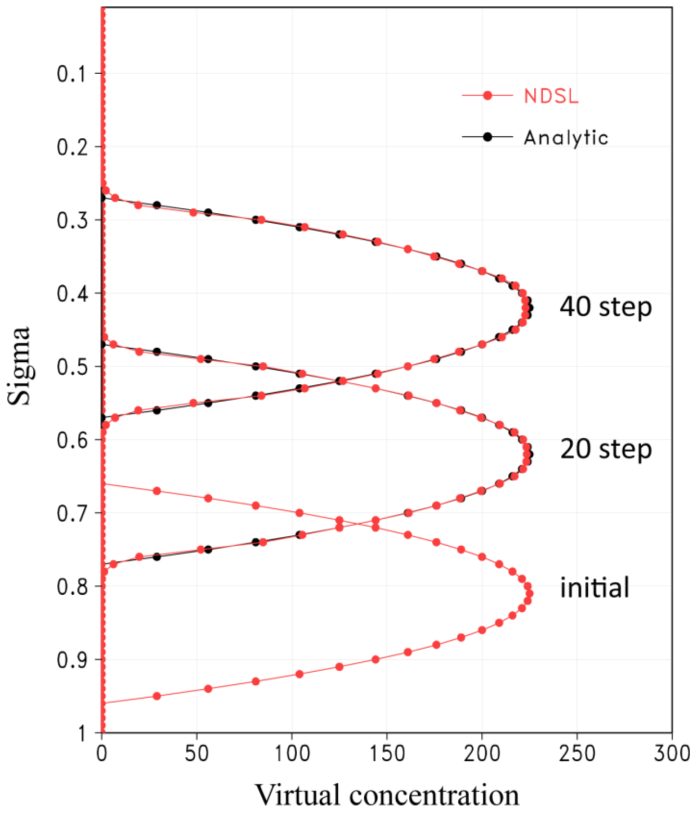


Figure 4. Virtual concentration from the idealized vertical advection experiment. The red and black lines indicate the transported concentration by the NDSL and the analytic solution, respectively.

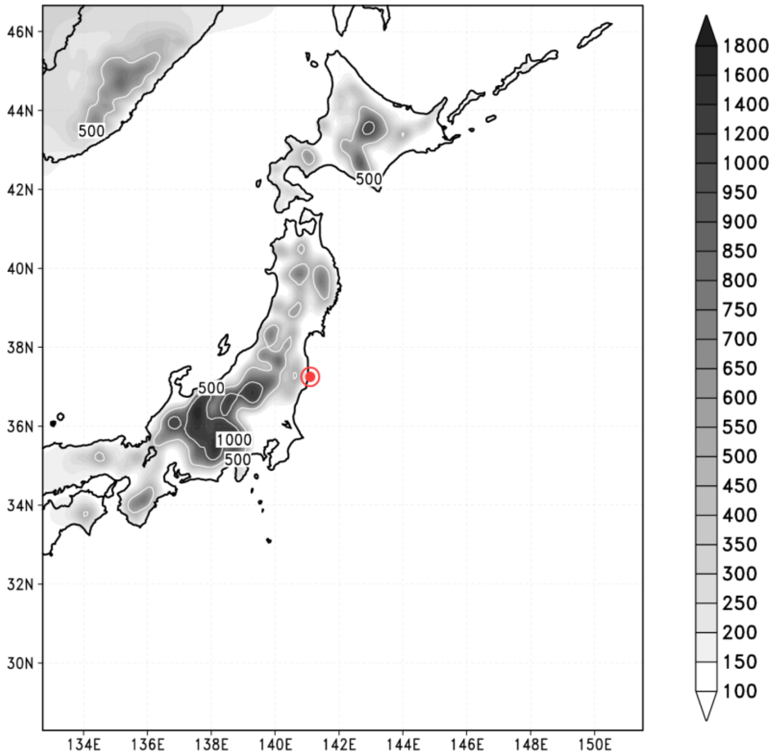
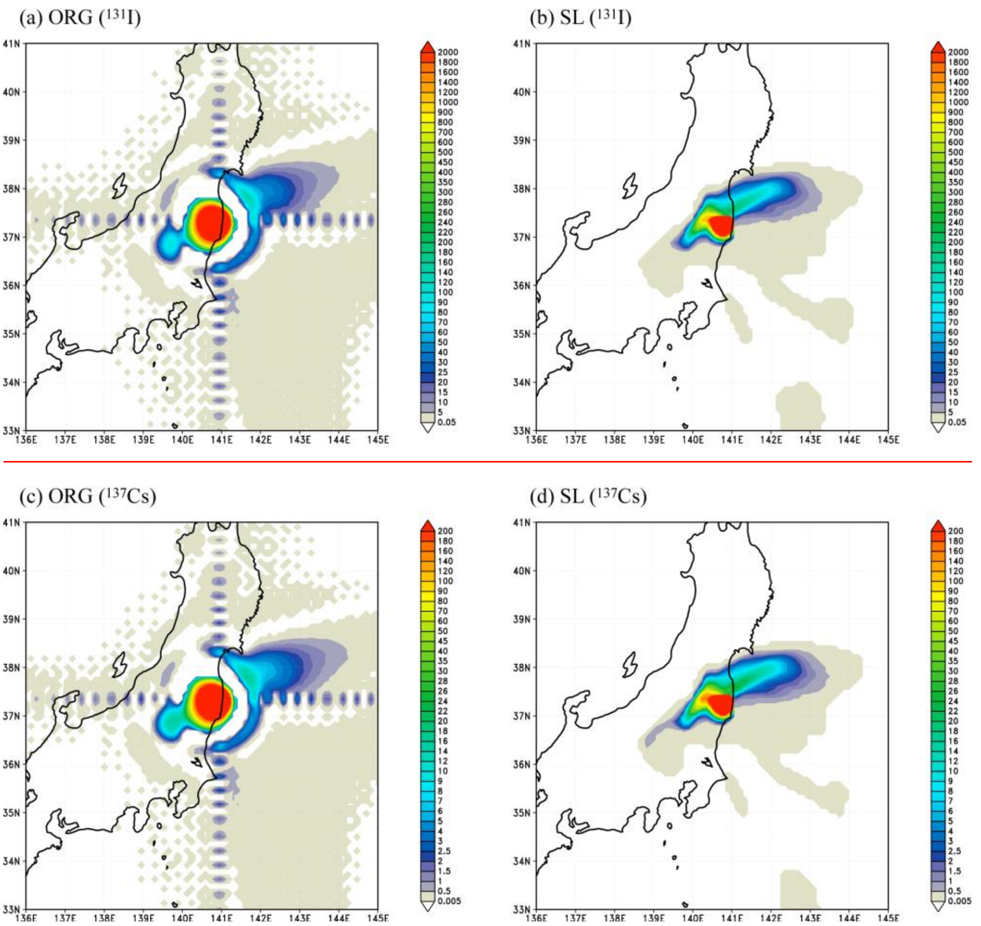


Figure 5. Experimental domain for the case study. The shaded values indicate orography (m). The red circle is the emission point, which is the location of the nuclear power plant in Fukushima.


(a) ORG (131I)
(b) SL (131I)
(c) ORG (137Cs)
(d) SL (137Cs)

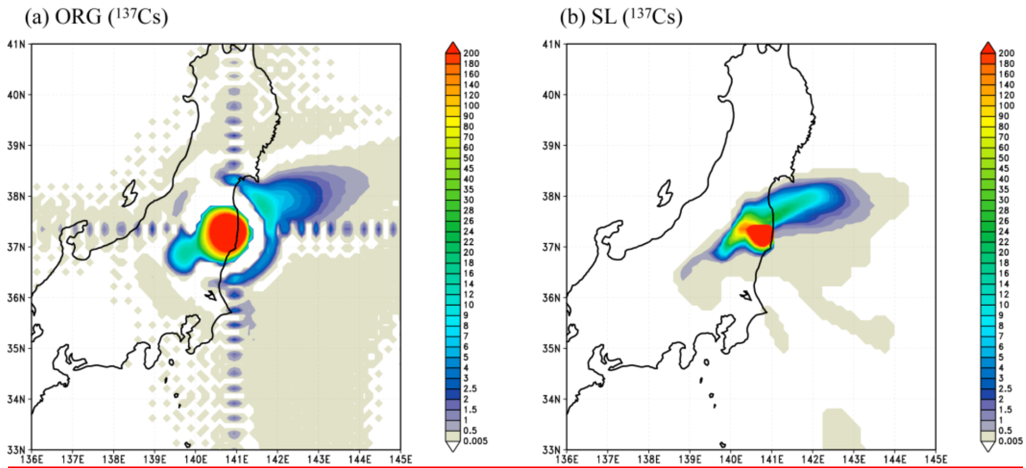
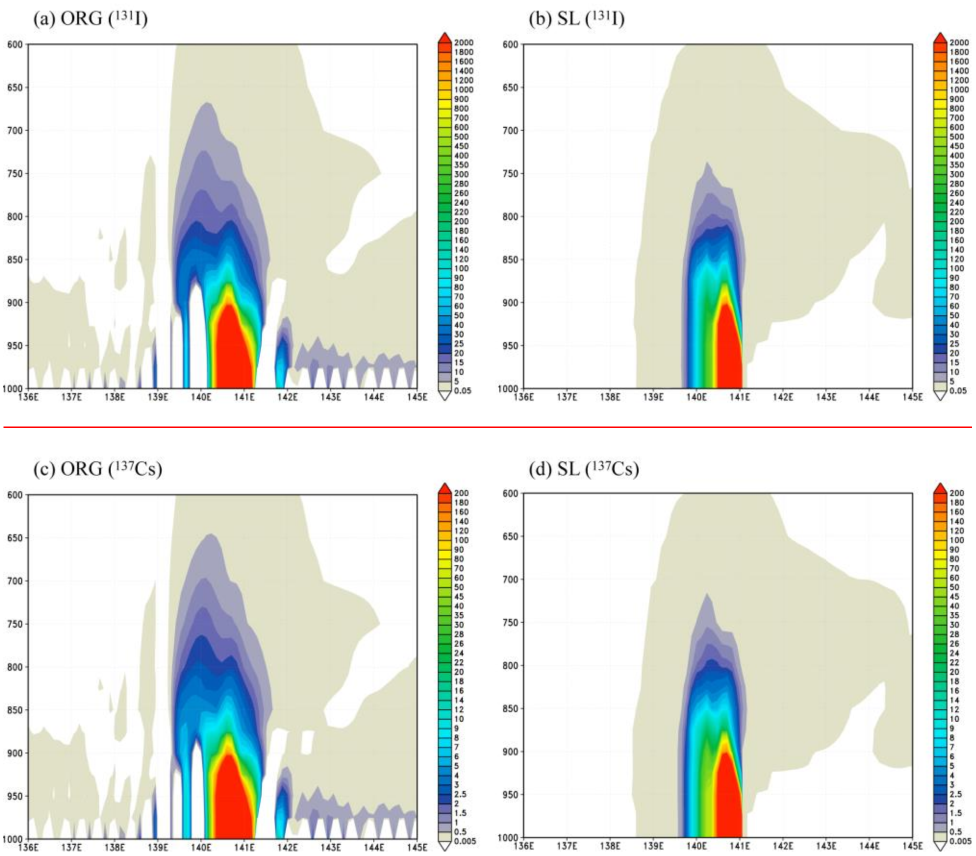

(a) ORG (137Cs)
(b) SL (137Cs)

Figure 6. Simulated column-integrated atmospheric radioactive tracers (tracer (cesium-137, kBq m^{-2}) at 12 UTC 15 March 2011.



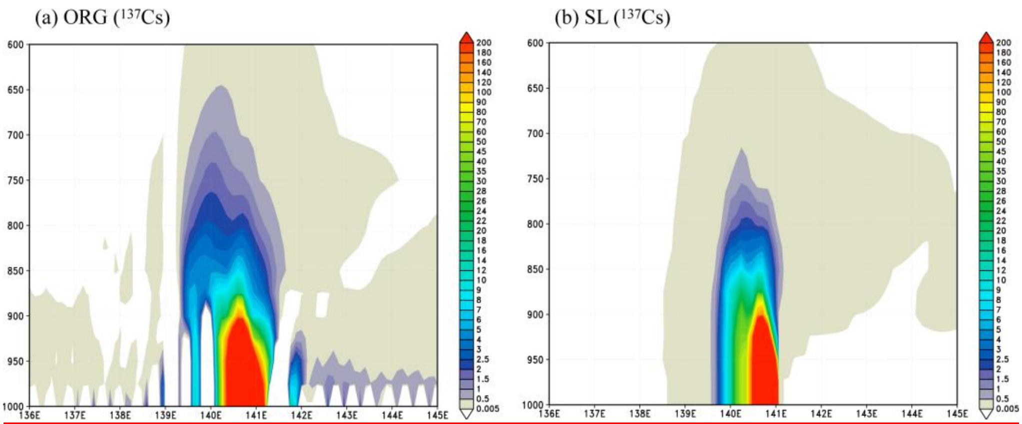


Figure 7. Simulated mixing ratio of radioactive tracers (cesium-137, Bq kg^{-1}) averaged over 36.5°N-37.5°N at 12 UTC 15 March 2011.

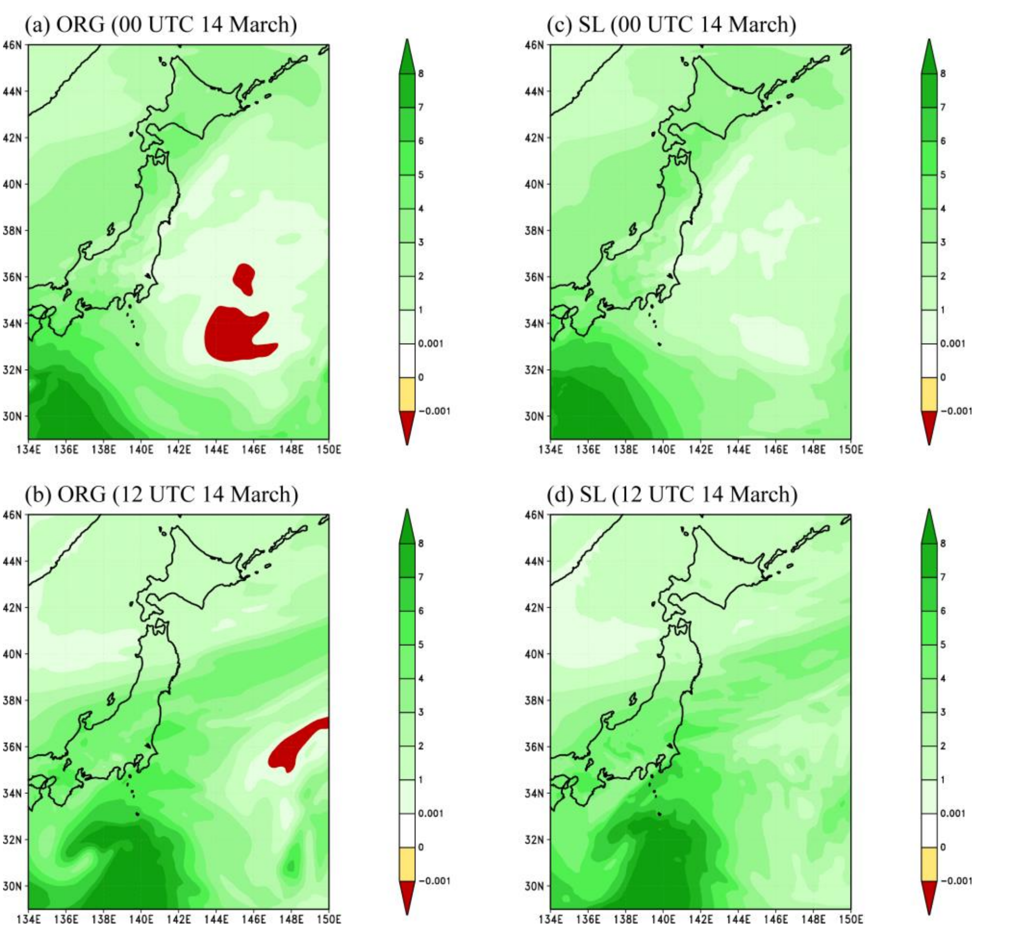
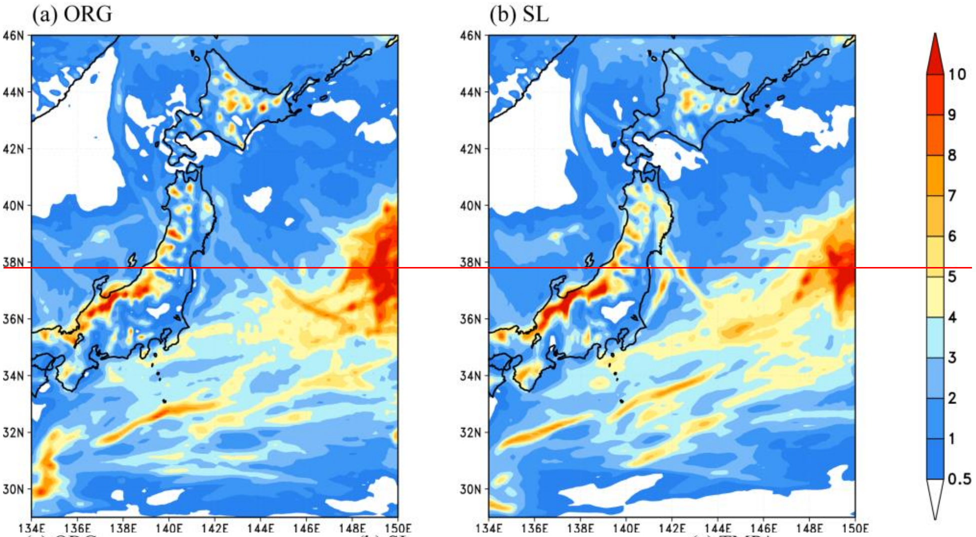


Figure 8. Specific humidity (g kg^{-1}) at 850 hPa from the (a, b) ORG and (c, d) SL runs at 00 and 12 UTC 14 March 2011, respectively.



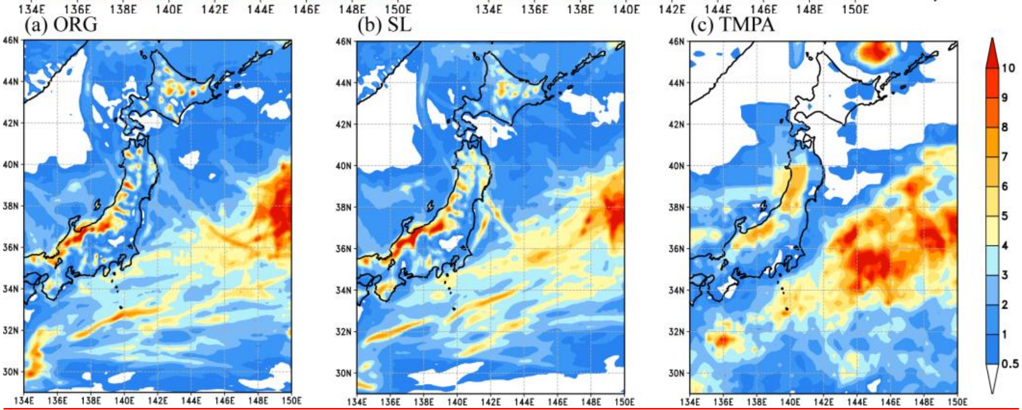


Figure 9. Average precipitation over the total integration period (16 days) from the (a) ORG ~~and~~run, (b) SL ~~experiments~~run, and (c) TMPA.