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 support that the NDSL advection of this study works properly in vertical direction for real-case configuration (i.e., non-uniform vertical grid spacing).

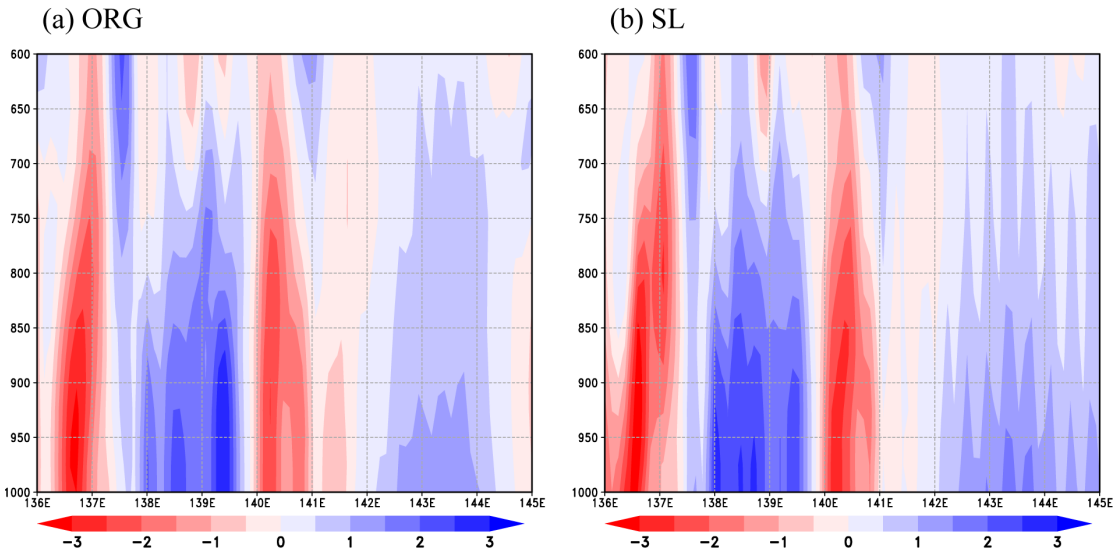

Fig. B1. Pressure vertical velocity (Pa s^{-1}) from (a) ORG run and (b) SL run averaged over 36.5°N-37.5°N at 12 UTC 15 March 2011.

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.