Dear Dr. Sørensen:

Thank you for your thoughtful comments to this paper. Your comments are very much in line with a complementary work to this paper, which should be ready for submission very soon. Here you will find our answers and manuscript updates in response to your review. The revised manuscript has also been posted as a supplemental document. Your comments are in black, while our responses are in *blue italics*.

Sincerely,

Alex Marti.

2. Dr. Sørensen Review

The fact that the NMMB/BSC-ASH model, which is intended for future operational use, involves two-way on-line coupling between meteorology and dispersion of volcanic ash is obviously an advantage and a step forward. However, the associated computational cost is probably sizable. There are large inherent uncertainties associated with forecasting dispersion of tephra, both regarding the source description and the meteorological parameters. The source model description encompasses the temporal evolution of the release of tephra, the ash column height and the initial vertical distribution of ash, all of which can fluctuate rapidly, as well as the ash particle size distribution. The uncertainty of numerical weather prediction can also be substantial with large effects on dispersion prediction, and a proper description requires use of costly ensemble prediction methods. Thus, the question is if the computational cost of carrying out two-way on-line coupling is justified against the costs of taking into account the uncertainties mentioned? I would appreciate that the authors include a related discussion of such a cost-benefit analysis.

This is a fair question. Thanks.

The manuscript has been updated to accommodate a preliminary discussion regarding the cost-benefit analysis of the NMMB/BSC-ASH over traditional off-line dispersal models. A complementary study to this work is currently undergoing to quantify these benefits comparing the on-line and the off-line coupling approaches in NMMB/BSC-ASH. The magnitude of the model forecast errors implicit in the off-line approach is then compared to that of the source description.
Section 5.6 (Page 19, lines 10-35):

"Employing on-line models for operational dispersal forecast requires larger computational resources and is not always feasible at all operational institutes. Nevertheless, due to the increase in computing power of modern systems, one can argue that such gradual migration towards stronger on-line coupling of NWPMs with TDMs poses a challenging but attractive perspective from the scientific point of view for the sake of both high-quality meteorological and volcanic ash forecasting.

The focus on volcanic aerosols integrated systems in operational forecast is timely. Experiences from other communities (e.g. air quality) have shown the benefits from two-way online meteorology-chemistry modeling. For example, the importance of the different feedback mechanisms for meteorological and atmospheric composition processes have been previously discussed for models developed in the USA (Zhang, 2008) and Europe (Baklanov et al., 2014). These benefits have been recently stressed by several studies covering the analysis of the aerosol-transport and aerosol-radiation feedbacks onto meteorology from the air quality model evaluation international initiative (AQMEII) in its phase 2 (Alapaty et al., 2012; Galmarini et al., 2015) and the EuMetChem COST Action ES1004 (EuMetChem, http://eumetchem.info)

Demonstrating these benefits however, require running the on-line model with and without feedbacks over extended periods of time. For the particular case of volcanic aerosols, further research is still required to quantify the benefits posed by on-line couple models over traditional off-line TTDM on both atmospheric transport and the radiative budget. The Barcelona Supercomputing Center is currently working to quantify these benefits with the NMMB/BSC-ASH model, and assess how the magnitude of the model forecast errors implicit in the off-line approach compares with other better-constrained sources of forecast error, e.g. uncertainties in eruption source parameters. Preliminary results from this study indicate that meteorology-transport inconsistencies from off-line models can be, in some cases, in the same order of magnitude that those associated to the eruption source parameters. In terms of computational cost, the computational efficiency of the NMMB/BSC-ASH meteorological core allows for on-line integrated operational forecasts employing an equivalent computational time than FALL3D for the same computational domain and number of processing cores."

Finally, the feedback effects of volcanic aerosols on the radiative budget (aerosol-radiation) are currently under investigation at the BSC. However, results from other aerosol studies indicate that these feedbacks are also significant in cases where the aerosol optical depth is ≥ 3. This would be the case, for example, for strong African and Mediterranean dust intrusions (e.g Pérez et al., 2006)*, heat waves or fires (e.g* Baró et al., 2017; Forkel et al., 2016).

Furthermore, I expect that the effect of on-line coupling is significant only fairly close to the eruption site, where the ash plume influences the radiation budget and the meteorological parameters. Please, comment.

Thanks for this comment. As pointed out by the reviewer, the feedback effect of volcanic aerosols on the radiative budget is especially important near the source term. However, feedback effects can also be significant for long-range transport when the aerosol optical depth is big (AOD ≥ 3). An example of this is discussed in Pérez et al. (2006)*, where the authors showed that, for a major dust outbreak over the Mediterranean on April 2002, the dust-radiation interaction scheme embedded into the NCEP/Eta NWP limited-area model increased accuracy for both atmospheric temperature and mean sea-level pressure forecasts across the computational domain.*

In addition, on-line coupling systems also have significant effects in the transport of volcanic aerosols (meteorology-transport feedback). This effect is important for both proximal and long-range simulations. For the proximal deposit, a representative particle advection during the first hours of the eruption is key to represent the transport and depositions of coarse particles. For the distal deposit, on-line couple models are capable to minimize the dispersion error accumulated by off-line models (from coupling intervals; i.e. time for which meteorological fluctuations are not explicitly resolved).

The NMMB/BSC-ASH model is optimized for running on an HPC facility by employing distributed-memory parallelization (MPI). However, modern and future HPC facilities are, and will be, based on multi- or many-core processors, and thus shared-memory parallelization and thread scalability, as well as vectorization (AVX), is essential for obtaining significant performance on future HPC facilities. The authors are encouraged to comment on the model's thread scalability properties, and on possibilities for using e.g. OpenMP and OpenACL on the model code.

The performance analysis of a parallel code can be a challenging task. This is especially true in operational forecast where there can be multiple performance bottlenecks caused from different fields.

Model parallelization in NMMB/BSC-ASH is based on the well-established Message Passing Interface (MPI) library. The computational domain is decomposed into sub-domains of nearly equal size in order to balance the computational load, where each processor is in charge to solve the model equations in one sub-domain. The numerical performance and scalability of the model are presented in Section 3.5 and 5.5 in the manuscript, respectively.

The performance analysis of the NMMB/BSC chemical transport model has also been evaluated to identify various bottlenecks. In particular, Markomanolis et al. (2014) *studied the differences between some model configurations of the model depending on the usage of extra modules. In this study they evaluated eight different topics (e.g. processor affinity, hardware encounters, domain decomposition, mapping, load imbalance issues, scalability, etc.) that could limit the scalability of the model. Their experiments used OpenMPI 1.5.4 and Intel Fortran 13.0.1. Their study identifies which computation parts of the code need to be improved and the possible reasons for the downgrade performance. Their work also illustrated, amongst other things, the importance of the processor affinity for computation intensive models and the domain decomposition across the participated nodes, and the generic load imbalance issues common for most models. The model performance could be improved through code vectorization and fix serialization procedures in the future.*

Additional efforts are also currently undergoing to use the programming model OmpSs in order to investigate and improve the performance of the NMMB/BSC chemical transport model model. The objective here is to convert some *computation phases to tasks and execute them efficiently by identifying the dependencies between them. Some preliminary results have been presented here:*

- Optimizing an Earth Science Atmospheric Application with the OmpSs Programming Model. George S. Markomanolis, Barcelona Supercomputing Center, PRACE Scientific and Industrial Conference 2014, Barcelona, Spain.
- Optimizing an Earth Science Atmospheric Application with the OmpSs Programming Model. G.S. Markomanolis, 16th HPC workshop on meteorology, ECMWF, Reading, UK, 2014

In the caption of Fig. 2, the word Europe should probably be replaced by South America.
Corrected- Thanks!

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