Title of Grant:
Development of Modal Aerosol Module in CAM5 for Biogeochemical Cycles

Type of report:
Final Technical Report

Name of the principal investigator:
Dr. Xiaohong Liu
University of Wyoming

Reporting Period:
06/1/2014 - 05/31/2017

Name and address of the recipient's institution:
Prof. Xiaohong Liu
Department of Atmospheric Science
University of Wyoming
Laramie, WY 82071
Tel: 307-766-3225
Email: xliu6@uwyo.edu

Grant number:
Award No. DE-SC0011611

Project Goal

This project aims at developing new capabilities for the Modal Aerosol Module in the DOE's E3SM model with the applications to the global biogeochemical cycle. The impacts of the new developments on model simulations of clouds and climate will be examined. There are thee objectives for this project study:

- Implementing primary marine organic aerosols into the modal aerosol module (MAM) and investigate effects of primary marine organic aerosols on climate in E3SM.
- Implementing dust speciation in MAM and investigate the effect of dust species on mixed-phase clouds through indirect effects in E3SM.
- Writing papers documenting the new MAM developments (e.g., MAM4 documentation paper, marine organic aerosol paper, dust speciation).

These objectives will be accomplished in collaborations with Drs. Phil Rasch, Steve Ghan, and Susannah Burrows at Pacific Northwest National Laboratory.

Project Accomplishments:

(1) Implemented primary marine organic aerosols into the modal aerosol module (MAM) and investigated their effect on climate in E3SM

Primary organic aerosol emitted from the marine biogeochemical activities may play an important effect on cloud properties, precipitation and climate over the remote oceanic regions. However, this type of aerosol has not been included in MAM and its climatic effects not quantified. In this project we implemented two new marine organic modes (MOM) on top of the 7-mode version of MAM (MAM7) to represent the marine organic aerosols in the Aitken- and accumulation-mode size ranges. There are five primary organic compounds in each MOM: polysaccharide, protein, lipid, humics, and fulvic acid, which generally have lower hygroscopicities than sea salt. By the aerosol microphysics (condensation and coagulation) these marine organic compounds will be transferred to the other modes in MAM7 (i.e., Aitken, accumulation and primary carbon modes). Therefore we are also adding marine organic compounds in these three modes of MAM7. This brings the number of aerosol modes to 9 and total number of aerosol species to 58 (as compared to 31 in MAM7).

We provided our new MAM version with two MOMs to PNNL (Susannah Burrows). She then linked the OCEANFILMS parameterization (Burrows et al. 2014) of primary marine organic aerosol emissions to the new MAM. We evaluated model simulation of marine organic aerosols with observations and investigated the impacts of marine organic aerosols on aerosols, clouds and climate in E3SM. Four sensitivity tests are conducted, in which organic emissions either add to or replace sea salt emissions (in mass and number), and are either internally or externally mixed with sea salt. The simulation with internally-mixed, added organics agrees best with observed seasonal cycles of organic matter in marine aerosol. In this configuration, marine organic aerosols contribute additionally up to 30 cm^{-3} to CCN concentrations (S = 0.1%) in the Southern Ocean boundary-layer (Figure 1). As a result, the shortwave radiative cooling by clouds is strengthened by -0.36 W m^{-2} in the global annual mean, and by more than -3.5 W m^{-2} in the summer over the Southern Ocean.

The implementation of marine organic aerosols and their impacts on clouds in E3SM have been documented in a journal article, ready to be submitted (Burrows, Easter, and Liu, et al. 2017). We have also presented these results in various meetings (e.g., AGU Fall meetings) and conferences.

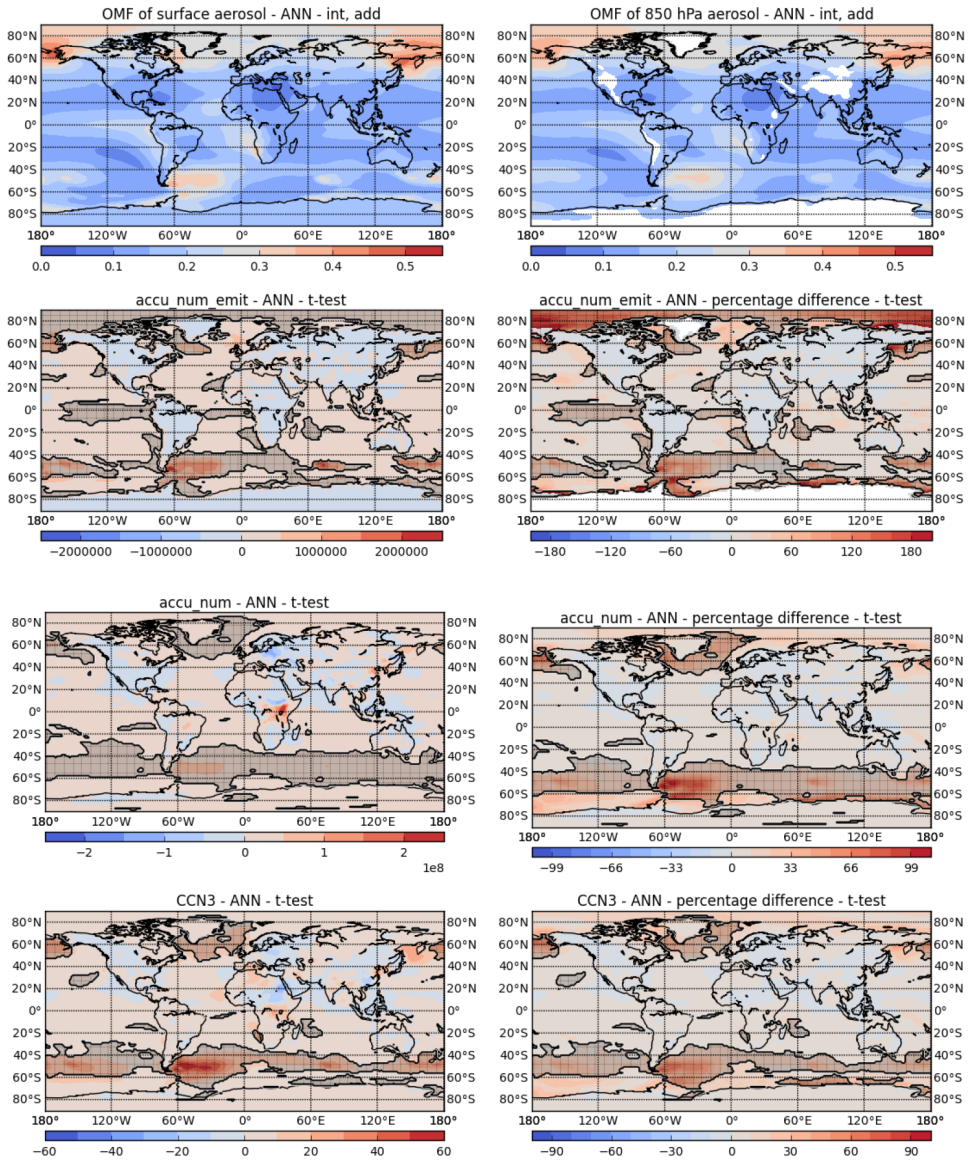

Figure 1. Modeled fields, and changes in modeled fields due to introduction of marine organic aerosol. Shaded regions outlined with black contours indicate regions where absolute differences are statistically significant by Welch's t-test at the $p < 0.1\%$ level. White space indicates missing values. Top row: Global annual mean organic mass fraction of accumulation-mode sea spray aerosol at surface (left) and 800 hPa (right). Second row: Global annual mean change absolute change (left) and percentage change (right) in accumulation mode number emissions. Third row: Global annual mean change absolute change (left) and percentage change (right) in accumulation mode number concentration in lowest atmospheric model level. Fourth row: Global annual mean absolute change (left) and percentage change (right) in CCN concentration at S=0.1% in lowest atmospheric model level.

(2) Implemented dust speciation in MAM and investigated effects of dust species on mixed-phase clouds through indirect effects in CAM5

Mineral dust plays a critical role in the Earth system by affecting radiation balance, modifying cloud properties, and providing the nutrition to ecosystems, etc. Although many of dust effects have been included in climate models, dust particles are generally treated as bulk species, neglecting the fact that dust radiative and ice nucleating properties depend strongly on their mineralogical composition.

We have implemented an online dust mineralogy in MAM for CAM5 by predicting eight dust components (illite, kaolinite, montmorillonite, hematite, quartz, calcite, feldspar, and gypsum) separately. Source maps of minerals in different soil types over the globe are derived from the mean mineralogical table (MMT) from Claquin et al. (1999). Then the dust optical properties are linked to the refractive indices of different dust components. Efficiencies of immersion, deposition and contact freezing of cloud droplets in mixed-phase clouds are linked to the ice nucleating minerals (e.g., K-feldspar) based on the parameterization derived from the observations (Atkinson et al. 2013).

CAM5 simulations have been conducted to investigate the impacts of dust speciation on cloud properties (e.g., cloud water path, cloud fraction) and radiative forcing. In one simulation, we tested the role of ice nucleation by K-feldspar mineral based on the parameterization by Atkinson et al. (2013), and compared it to two other simulations using the mineralogy-independent parameterizations for desert dust (Niemand et al. 2012; DeMott et al. 2010). Large differences in modeled ice nucleating particle concentrations are found among these parameterizations (Figure 2). The impacts on clouds and climate are also investigated.

We have provided our source code of dust speciation to Dr. Natalie Mahowald at Cornell University for her DOE ESM project to investigate the role of mineral dust in biogeochemical cycles.

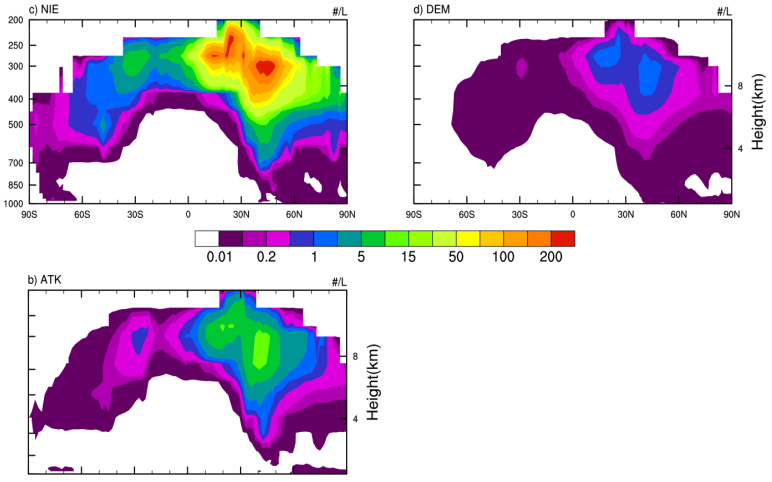

Figure 2. Modeled dust INP number concentrations with three ice nucleation parameterizations in CAM5 (Niemand: upper left; DeMott: upper right; and Atkinson: lower panel).

(3) Wrote papers documenting the new MAM developments (e.g., MAM4 documentation paper, marine organic aerosol paper)

We have written and published the MAM4 documentation paper (Liu et al. 2016). The MAM4 aerosol scheme has been adopted by CESM2 and E3SM models.

We have finished a paper documenting the marine organic aerosol and its indirect effect, for which PNNL is the lead (Burrows, Easter, and Liu, et al. 2017).

We are working on writing one paper on dust speciation and impacts on clouds and climate through indirect effects.

Peer-Reviewed Publications as a result of Funding Support from This Project

Liu, X., P.-L. Ma, H. Wang, S. Tilmes, B. Singh, R. C. Easter, S. J. Ghan, and P. J. Rasch (2016), Description and evaluation of a new 4-mode version of Modal Aerosol Module (MAM4) within version 5.3 of the Community Atmosphere Model, *Geoscientific Model Development*, *9*, 505–522, doi:10.5194/gmd-9-505-2016.

Burrows S., R. C. Easter, **X. Liu**, P.-L. Ma, H. Wang, S. M. Elliott, B. Singh, K. Zhang, and P. J. Rasch, OCEANFILMS organic sea spray emissions – Part 1: implementation and impacts on clouds, to be submitted, 2017.

Ban-Weiss, G. A., L. Jin, S. E. Bauer, R. Bennartz, **X. Liu**, K. Zhang, Y. Ming, H. Guo, and J. H. Jiang (2014), Evaluating clouds, aerosols, and their interactions in three global climate models using satellite simulators and observations, *Journal of Geophysical Research*, *119*, 10,876–10,901, doi:10.1002/2014JD021722.

Das, S., H. Bian, Harshvardhan, M. Chin, G. Curci, T. Mielonen, K. Zhang, H. Wang, and **X. Liu** (2017), Biomass burning aerosol transport and vertical distribution over the South African-Atlantic region, *Journal of Geophysical Research*, *122*, 6391–6415, doi:10.1002/2016JD026421.

Kipling, Z., P. Stier, C. E. Johnson, G. W. Mann, N. Bellouin, S. E. Bauer, T. Bergman, M. Chin, T. Diehl, S. J. Ghan, T. Iversen, A. Kirkevåg, H. Kokkola, **X. Liu**, G. Luo, T. van Noije, K. J. Pringle, K. von Salzen, M. Schulz, Ø. Seland, R. B. Skeie, T. Takemura, K. Tsigaridis, and K. Zhang (2016), What controls the vertical distribution of aerosol? Relationships between process sensitivity in HadGEM3–UKCA and inter-model variation from AeroCom Phase II, *Atmospheric Chemistry and Physics*, 16, 2221–2241, doi:10.5194/acp-16-2221-2016.

Komurcu, M., T. Storelvmo, I. Tan, U. Lohmann, Y. Yun, J. E. Penner, Y. Wang, **X. Liu**, and T. Takemura (2014), Inter-comparison of the cloud water phase among global climate models, *Journal of Geophysical Research*, *119*, 3372–3400, doi:10.1002/2013JD021119.

Ma, P.-L., P. J. Rasch, M. Wang, H. Wang, S. J. Ghan, R. C. Easter, W. I. Gustafson Jr., **X. Liu**, Y. Zhang, and H.-Y. Ma (2015), How does increasing horizontal resolution in a global climate model improve the simulation of aerosol-cloud interactions?, *Geophysical Research Letter*, *42*, 5058–5065, doi:10.1002/2015GL064183.

Scanza, R. A., N. Mahowald, S. J. Ghan, C. S. Zender, J. F. Kok, **X. Liu**, Y. Zhang, and S. Albani (2015), Modeling dust as component minerals in the Community Atmosphere Model: Development of framework and impact on radiative forcing, *Atmospheric Chemistry and Physics*, *15*, 537–561, doi:10.5194/acp-15-537-2015.

References in the Report

Atkinson, J.D., B.J. Murray, M.T. Woodhouse, T.F. Whale, K.J. Baustian, K.S. Carlslaw, S. Dobbie, D. O'Sullivan and T.L. Malkin: The importance of feldspar for ice nucleation by mineral dust in mixed-phase clouds, *Nature* 498, 355-358, doi:10.1038/nature12278, 2013.

Burrows, S. M., Ogunro, O., Frossard, A. A., Russell, L. M., Rasch, P. J., and Elliott, S. M.: A physically based framework for modeling the organic fractionation of sea spray aerosol from bubble film Langmuir equilibria, *Atmos. Chem. Phys.*, 14, 13601-13629, https://doi.org/10.5194/acp-14-13601-2014, 2014.

Burrows S., R. C. Easter, X. Liu, P.-L. Ma, H. Wang, S. M. Elliott, B. Singh, K. Zhang, and P. J. Rasch, OCEANFILMS organic sea spray emissions – Part 1: implementation and impacts on clouds, to be submitted, 2017.

Claquin, T., Schulz, M., and Balkanski, Y.: Modeling the mineralogy of atmospheric dust sources, *Journal of Geophysical Research*, 104, 22,243-222,256, 1999.

DeMott, P. J., A. Prenni, X. Liu et al.: Predicting global atmospheric ice nuclei distributions and their impacts on climate. *Proceedings of the National Academy of Sciences of USA, 107*, 11217-11222, doi:10.1073/pnas.0910818107, 2010.

Liu, X., P.-L. Ma, H. Wang, S. Tilmes, B. Singh, R. C. Easter, S. J. Ghan, and P. J. Rasch, Description and evaluation of a new 4-mode version of Modal Aerosol Module (MAM4) within version 5.3 of the Community Atmosphere Model, *Geoscientific Model Development*, *9*, 505–522, doi:10.5194/gmd-9-505-2016, 2016.

Niemand, M., et al.: A Particle-Surface-Area-Based Parameterization of Immersion Freezing on Desert Dust Particles. *J. Atmos. Sci.*, 69, 3077–3092, 2012. doi: http://dx.doi.org/10.1175/JAS-D-11-0249.1, 2012.