

**Improving Cloud Microphysics and Their Interactions with Aerosols in the NCEP
Global Models**

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1. Main goals of the project

Overarching goal of this MAPP-CTB project is to improve the representation of aerosol processes, cloud microphysics, and aerosol-cloud-radiation interaction in NCEP global models.

While understanding the climate impact of the complex cloud-aerosol-radiation interactions remains a major frontier in climate sciences, there have been significant processes in developing process-level representations of clouds and aerosols as well as in understanding the processes relevant to aerosol-cloud-radiation interactions. This MAPP-CTB project proposes to upgrade NOAA Environmental Modeling System (NEMS) Global Forecast System (GFS) physics suite by adapting NASA Global Modeling and Assimilation Office (GMAO) cloud/aerosol package, i.e., a double-moment cloud microphysics scheme (MG, Morrison and Gettleman, 2008; Barahona et al. 2014) and a multimodal and double-moment modal aerosol model (MAM-7, Liu et al., 2012). Both MG and MAM schemes are developed and implemented in the Community Atmosphere Model (CAM5.1), the atmospheric component of the Community Earth System Model (CESM) at the National Center for Atmospheric Research (NCAR). The efforts to implement GMAO's physically-based cloud/aerosol package into NCEP global models in turn leverage scientific advances by a broad climate research community.

2. Results and Accomplishments

NEMS Framework

NCEP is developing NEMS (<http://www.emc.ncep.noaa.gov/index.php?branch=NEMS>) with a component-based architecture following the Earth System Modeling Framework (ESMF, see <http://www.earthsystemmodeling.org>). The development of NEMS aims to develop a common superstructure for NCEP production suite. Currently the Global Spectrum Model (GSM), the B-grid version of the Nonhydrostatic Multiscale Model (NMM-B), Flow-following finite-volume Icosahedral Model (FIM), and Finite-Volume Cubed-Sphere (FV3) dynamic core have been placed within the NEMS framework. The first implementation of NEMS at NCEP is in the NAM (North American Mesoscale) modeling suite, using NEMS NMM-B. The second implementation is to run NEMS GFS Aerosol Component (NGAC, NEMS GSM with prognostic aerosols) for global

aerosol forecasts. The latest implementation is to use NEMS GSM as the atmospheric forecast model for global forecast and analysis system.

This project made extensive code development in NEMS GSM. This includes:

- Implement a multimodal and double-moment MAM-7 as a potential upgrade to replace the operational Goddard Chemistry Aerosol Radiation and Transport (GOCART) scheme (Colarco et al., 2010).
- Implement a double-moment cloud microphysics scheme (MG) as an option that would replace the operational Zhao-Carr cloud microphysics scheme (Zhao and Carr, 1997).
- Couple among cloud micro and macro physics, radiation, aerosol physicochemical properties, and cloud properties

The team has completed primary proposed tasks: the implementation of MAM-7 aerosol scheme and MG cloud microphysics scheme into NEMS GSM. The two new schemes have been tested individually (uncoupled) initially, and then interactively (coupled) in the later phase of project. Additional cloud diagnostic fields have been added to NEMS GSM, including liquid cloud water path, ice cloud water path, cloud optical depth, and cloud emissivity. A new option for prescribed GOCART aerosol fields has been added to NEMS GSM. This new option makes NEMS GSM aerosol-aware, as aerosol optical properties and cloud condensation nuclei and ice nuclei (CCN/IN) activation can be determined from prognostic aerosols (from internal tracer arrays) or prescribed aerosols (from external files).

NCEP chosen a coarse-grained design in NEMS. Only large pieces of the models are modularized with ESMF components with no intrusion into parameterization and parallelization levels. For NEMS GSM, there are separate ESMF-based dynamics and physics components, whereas dynamics and physics are combined into one ESMF component for NEMS NMM-B. GMAO, on the other hand, chosen a fine-grained component design in Goddard Earth Observing System Model, version 5 (GEOS-5). ESMF components are used down to the parametrization level. For instance, physics and chemistry are ESMF components and MG and MAM-7 code are ESMF components as well. The differences between fine-grained versus coarse-grained system design

not only affect the initial implementation (discussed in this section) but also affect upgrade and code synchronization down the road (discussed in section 4).

MAM-7 implementation

MAM-7 is capable of simulating the aerosol size distribution and both internal and external mixing between aerosol components. It treats numerous complicated aerosol processes and aerosol physical, chemical, and optical properties in a physically-based manner. Seven aerosol modes are considered, including Aitken, accumulation, primary carbon, fine sea salt, fine dust, coarse sea salt, and coarse dust. The aerosol components and microphysics for these modes are illustrated in Figure 1.

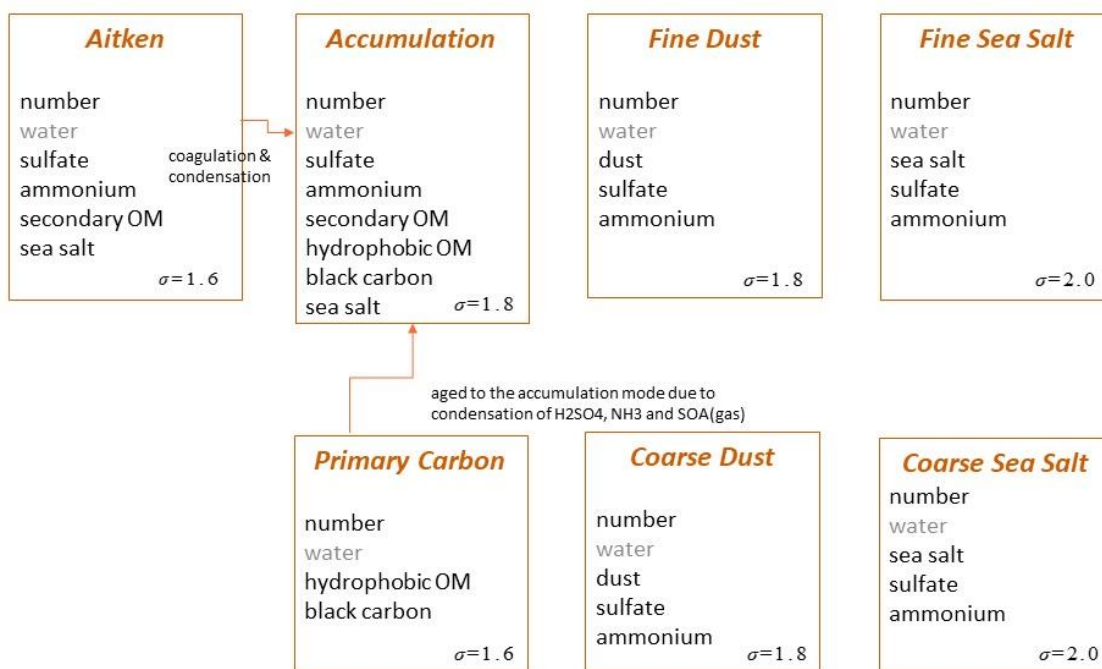


Figure 1. Aerosol components and microphysics processes represented in the MAM7 model.

An ESMF compliant MAM-7 aerosol module has been incorporated into GMAO's GEOS-5 and is later implemented into NCEP's NEMS GSM. In GEOS-5, an ESMF-based GEOS-Chem component is developed as the comprehensive chemistry suite which includes multiple chemistry modules, e.g., GOCART, MAM-7, AChem (gas and aqueous phase chemistry), CARMA (sectional aerosol model), and PCHEM (parameterized stratosphere chemistry). In GOCART, the sulfate module (also an ESMF component) considers simple sulfur chemistry to account for

oxidation of SO₂ and dimethylsulfide (DMS) from anthropogenic and natural sources, using prescribed OH, NO₃, and H₂O₂ radicals. In MAM-7, only aerosol processes are considered (shown in Fig. 1), and sulfate production from sulfur-related chemical processes is determined from its sibling component, ACHEM. Therefore, the MAM-7 and ACHEM are implemented together as an option to replace GOCART.

ESMF-based coupling approach is also undertaken by NCEP. In NGAC (Lu et al., 2016), ESMF couplers are developed to couple NEMS GSM with GOCART. In this project, an ESMF-based component (called NCEP_Chem) was developed to wrap around GMAO's GOES-Chem. ESMF coupler, developed to couple NEMS GSM with GOCART, is now used to couple with NCEP_Chem after minor code revision (e.g., adding these fields needed by MAM-7). While the architecture could allow NEMS GSM to run full suite of GMAO's chemistry suite, only GOCART

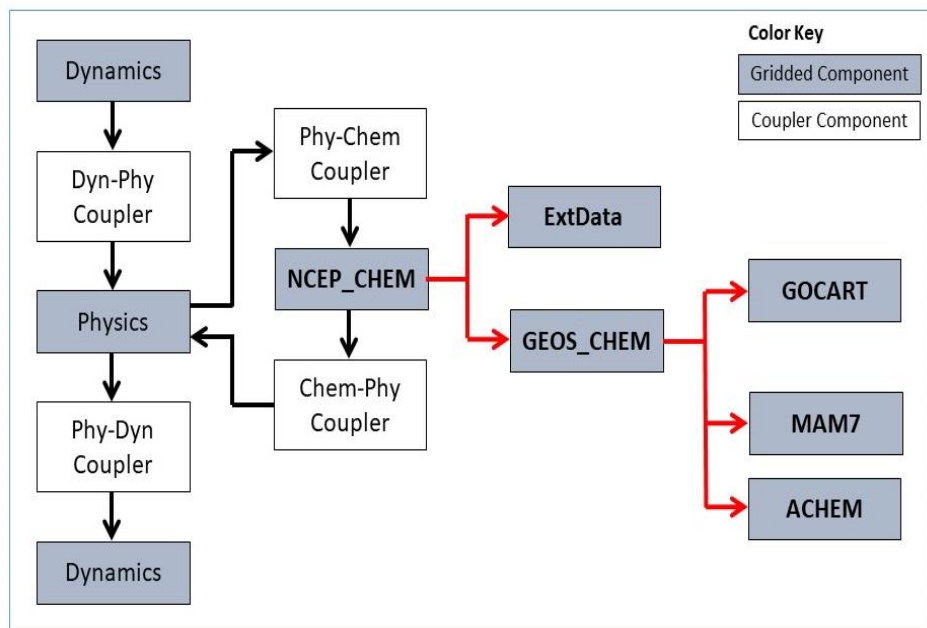


Figure 2 Primary run stream of NEMS GSM

and (MAM-7, ACHEM) are tested. Primary integration run stream is illustrated in Figure 2. The NCEP_Chem component contains GEOS_Chem and ExtData components. ExtData is an ESMF component used to read in emissions at any horizontal and temporal resolution.

GEOS_Chem within NCEP_Chem contains only GOCART, MAM-7 and ACHEM. Other chemistry modules not ported in NEMS GSM are compiled as stub on-the-fly. The users can invoke either GOCART or (ACHEM, MAM-7) at the run time using the same NEMS GSM executable.

MG implementation

The cloud microphysics scheme in GEOS-5 is a double-moment cloud microphysics scheme considering the evolution of ice and liquid mass mixing ratio and number concentration (Morrison and Gettelman 2008; Barahona et al., 2014). It explicitly treats processes of condensation, evaporation, collection, melting, freezing, and sedimentation (Figure 3). Cloud droplet and ice crystal production rates are computed considering the aerosol properties, temperature, and the

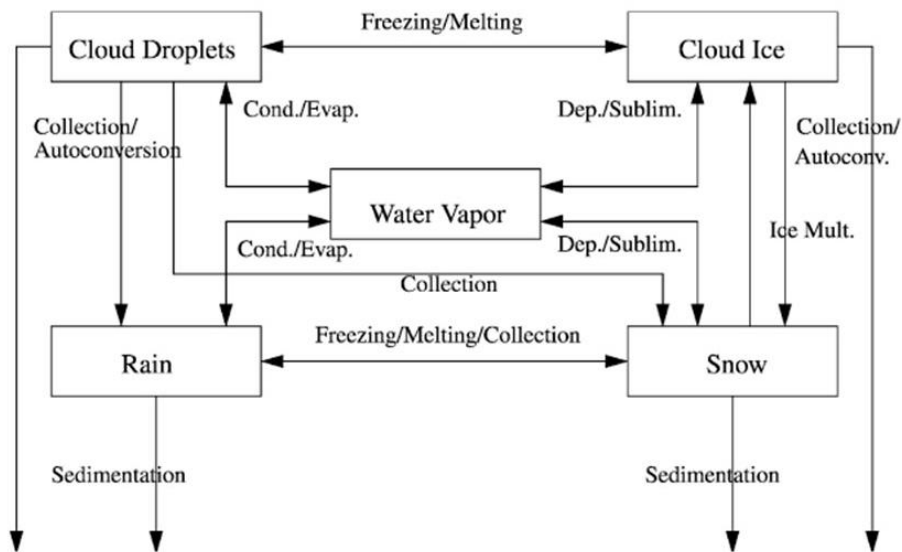


Figure 3 Processes represented in the MG cloud microphysics scheme

subgrid-scale dynamics.

Cloud droplet activation is computed linking explicitly to the aerosol composition and size distribution (Fountoukis and Nenes, 2005). Similarly, ice crystal nucleation is treated using a physically-based analytical approach (Barahona and Nenes 2009). Homogeneous

freezing of cloud droplets and haze particles as well as heterogeneous freezing of ice nuclei in the immersion, and contact modes are accounted for.

The MG scheme provided by GMAO has been implemented into NEMS GSM. The approach undertaken for MG implementation is different from the approach for MAM-7 implementation. MAM-7 implementation is built in modular form and leverages ESMF infrastructure, as discussed above. In contrast, all ESMF code in GMAO's MG scheme has been stripped away, allowing MG to be incorporated into NEMS GSM's physics suite where all parameterization routines are coded in Fortran.

The upgrade in how cloud microphysical processes are represented in NEMS GSM lead to additional development work (Figure 4). For instance, the MG scheme has been coupled with PDF-based cloud scheme (Simplified Higher-Order Closure (SHOC)) and convective parameterization (Relaxed Arakawa Schubert (RAS), Moorthi and Suarez. 1992). While the project aims to enable CCN/IN activation in cloud microphysics to be driven by aerosol size and composition provided by MAM-7, the MG development work has been using similar parameters diagnosed from the bulk GOCART scheme. Note the MG implementation has been accelerated by the NWS internal Research-to-Operation (R2O) project led by Co-I Dr. Shrinivas Moorthi.

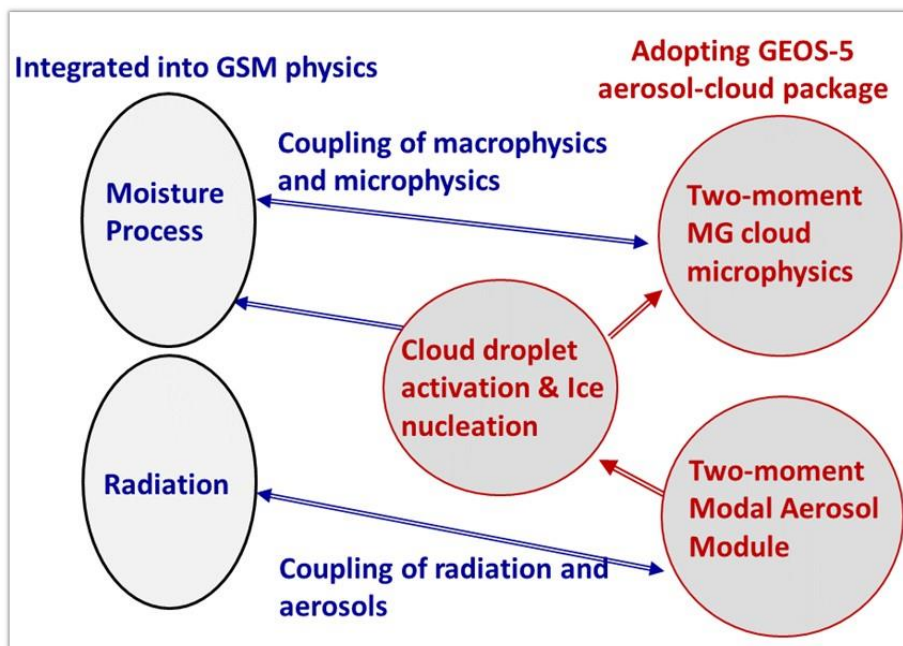


Figure 4 Coupling between GEOS-5 aerosol-cloud package and NEMS GSM physics suite

Extensive code development for bringing in MG into NEMS GSM and coupling MG with other physics in NEMS GFS physics suite are made by Dr. Moorthi's team while this project has been focused on coupling of the aerosol physicochemical

properties to cloud formation through CCN/IN activation and investigating aerosol-cloud interaction through a series of NEMS GSM experiments (see below).

NEMS GSM experiments – aerosol-cloud interaction

NEMS GSM experiments are conducted for selected cases, including 2014 New York snow storm, 2016 Louisiana flooding and 2016 Hurricane Matthew. Here we present the results for the 2016 Louisiana flooding case. T574 L64 NEMS GSM experiments are conducted for the Aug 8 – 17, 2016 period. The NEMS GSM configuration is same as the operational NGACv2 (NEMS GSM with prognostics GOCART turned on) except dynamics is changed from Eulerian to semi-

Lagrangian and resolution is increased from T126 (~ 100km) to T574 (~35km). Initial conditions for these experiments are taken from operational Global Data Assimilation System at T1534 (~ 13 km) except for aerosol fields which are determined from NGACv2 at T126. Three scenarios are considered: (1) the CTRL run with Zhao-Carr cloud microphysics, 2) the MG_NoAER run with MG cloud microphysics without aerosol activation, and (3) the MG_AER run with MG cloud microphysics with aerosol activation. Note the aerosol attenuation in RRTMG radiation module (Mlawer et al. 1997, Iacono et al. 2000, Clough et al. 2005) is determined from the OPAC climatology based on Hess et al. (1998) (the operational configuration), allowing this study to focus on aerosol-cloud interaction.

Figure 5 shows the global-averaged daily-mean cloud fraction from the three NEMS GSM runs,

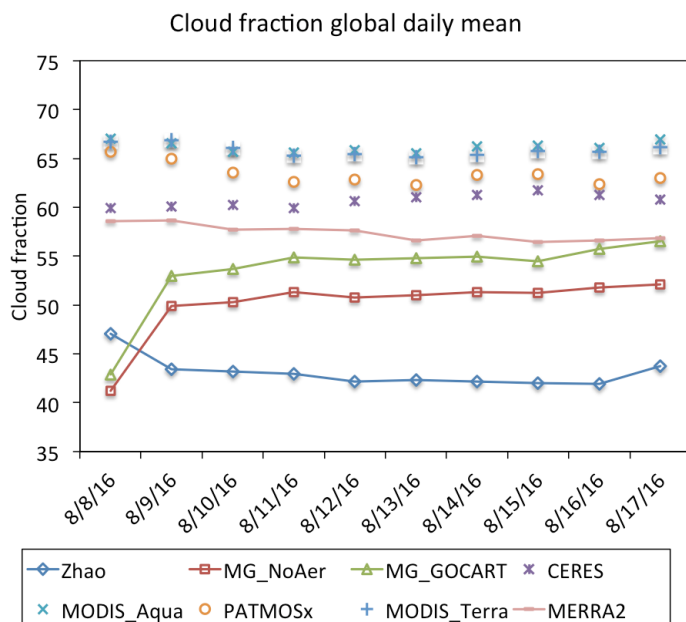


Figure 5 Global daily mean cloud fraction from NEMS GSM experiments, MERRA2, and satellite products (MODIS, CERES, PATMOSx) for Aug 8-17, 2016.

compared with reanalysis from NASA MERRA2 (Modern-Era Retrospective analysis for Research and Applications, Version 2) and satellite-derived cloud products from PATMOS-x (Pathfinder Atmospheres-Extended), MODIS (Moderate Resolution Imaging Spectroradiometer), and CERES (Clouds and the Earth's Radiant Energy System). Overall, the cloud fraction from the three NEMS GSM experiments shows low biases compared to MERRA2 reanalysis and satellite estimates. The low bias in cloud fraction is improved as the model physics suite is upgraded to the MG scheme. Previous studies comparing GFS (GSM without NEMS framework) with International Satellite Cloud Climatology Project (ISCCP) also show global underestimation in total cloud cover.

Zonal averaged cloud fraction as a function of latitude from NEMS GSM runs, MERRA2, and satellite products is shown in Figure 6. Overall NEMS GSM has better agreement with

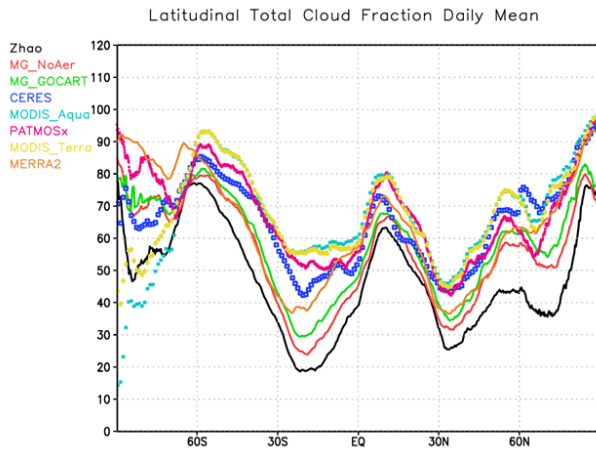


Figure 6 Zonal averaged cloud cover from NEMS GSM, MERRA2, and satellites (CERES, MODIS, PATMOSx)

observations and reanalysis in north tropical region (the equator to 30N). The CTRL run has consistently lower cloud cover than other two NEMS GSM runs with MG scheme. The largest discrepancy is found around north-hemisphere mid-latitude area and south-hemisphere polar region. The MG_AER run shows better agreement with MERRA2 and satellite observations. The results presented here (higher cloud fraction in MG results than CTRL but still lower than satellite retrievals)

are consistent with GEOS-5 results presented in Barahona et al. (2014).

Figure 7 shows high-level cloud optical depth from three NEMS GSM runs averaged for the Aug 10-17, 2016 period, compared with CERES estimates. All three model runs have lower high-level cloud optical depth compared with the CERES estimates. The CTRL run has the lowest cloud optical depth. The MG_NoAER and MG_AER run have similar spatial pattern, suggesting the improvement in cloud optical depth is mainly resulted from the change in cloud microphysics scheme, not in aerosol activation.

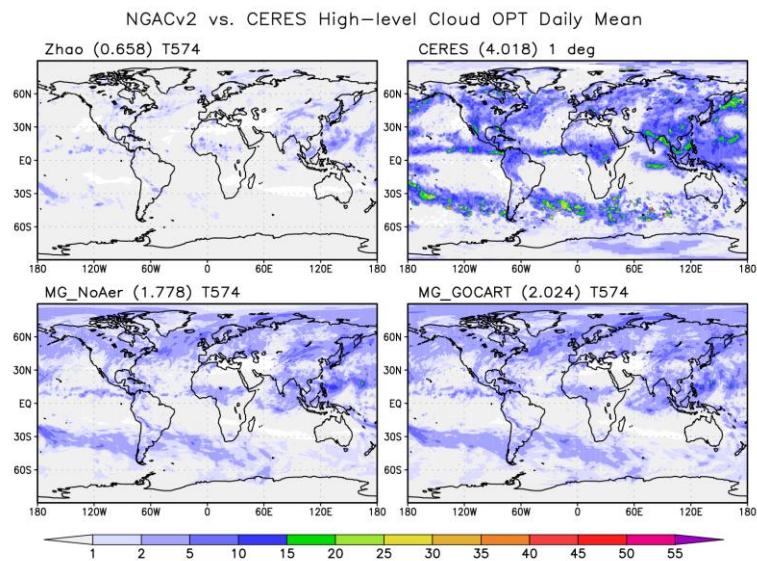


Figure 7 High-level cloud optical depth from NEMS GSM runs and CERES estimates, averaged for August 10-17, 2016

Latitude-height cross section of zonal mean liquid and ice cloud mas mixing ratios is displayed in Figure 8. While the Zhao-Carr scheme only has mixed-phase cloud condensate, the MG scheme considers ice and liquid separately. Both MG_NoAER and MG_AER show similar latitudinal

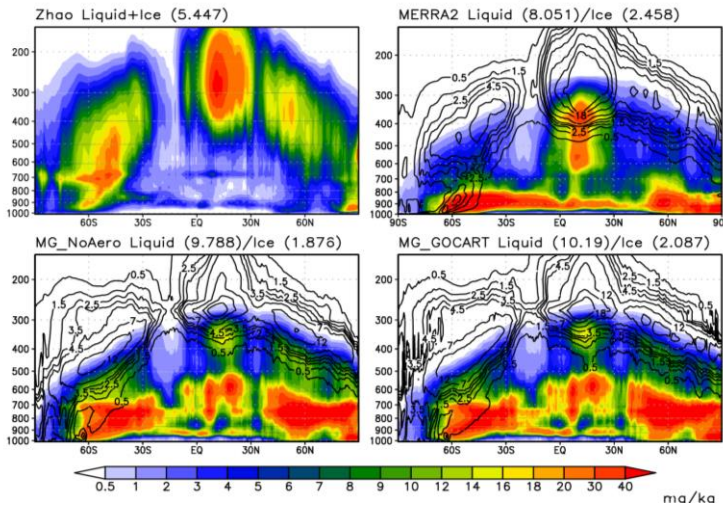


Figure 8 Cross section of zonal mean liquid and ice cloud mass mixing ratios for NEMS GSM runs and MERRA2

variations, especially for liquid cloud. At high altitudes MG_NoAER has lower [higher] ice cloud mass mixing ratios than MG_AER in the tropical region [mid-latitude region]. When compared with MERRA2, MG_AER has better agreement than MG_NoAER in the tropical region. Too much tropical high cloud is produced in the CTRL run. This feature is not found in MG runs and

MERRA2.

Despite the improvement in cloud properties by adopting the MG scheme, the impact of physics upgrade on precipitation is insignificant for this case. Figure 9 shows the daily precipitation for Aug 13 2016 from the three NEMS GSM runs compared with Climate Prediction Center (CPC) rain gauge observations. Overall, the model predicted precipitation is low compared with rain gauge and rain band observed at Texas and Oklahoma is not captured by the model regardless of physics configuration.

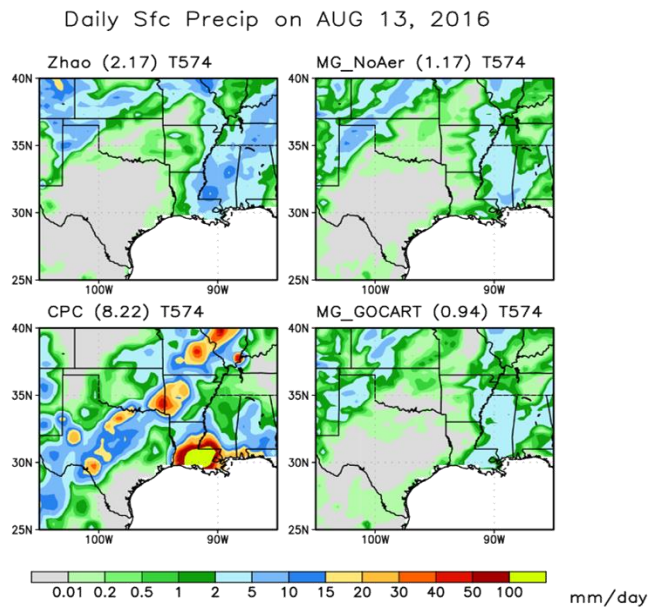


Figure 9 Daily precipitation for CTRL, MG_NoAER, MG_AER runs, compared with CPC rain gauge observations for Aug 13, 2016.

The new implementation resulted in a general model improvement in cloud properties. Cloud droplet and ice crystal number concentrations are now available as prognostic fields. However better cloud fields do not necessary lead to better weather prediction. Some tuning and adjustments

will be needed. The need for model refinement in turn calls for the need to enhance the model evaluation and verification package. The traditional GFS verification package is not sufficient to evaluate these physically-based schemes. For instance, cloud related diagnostics was not outputted in the operational GFS and has been added to NEMS GSM. Observation-based diagnosis package is needed to examine whether the model with improved aerosol-cloud package better capture the aerosol/cloud properties and the processes relevant to aerosol-cloud-radiation interaction.

NEMS GSM experiments – GOCART versus MAM-7

Two NEMS GSM experiments with different aerosol configuration are conducted for 2015 Aug-Oct period. One experiment invokes the GOCART option (the GOCART run) and the other experiment invokes ACHEM and MAM-7 (the MAM-7 run). The manuscript in preparation will be based on the results for the 2016 January to December period.

Figure 10 shows the 3-hourly column mass density, averaged from Aug to Oct, 2015, for dust and organic carbon aerosols from the MAM-7 run and the corresponding MERRA2 analysis fields.

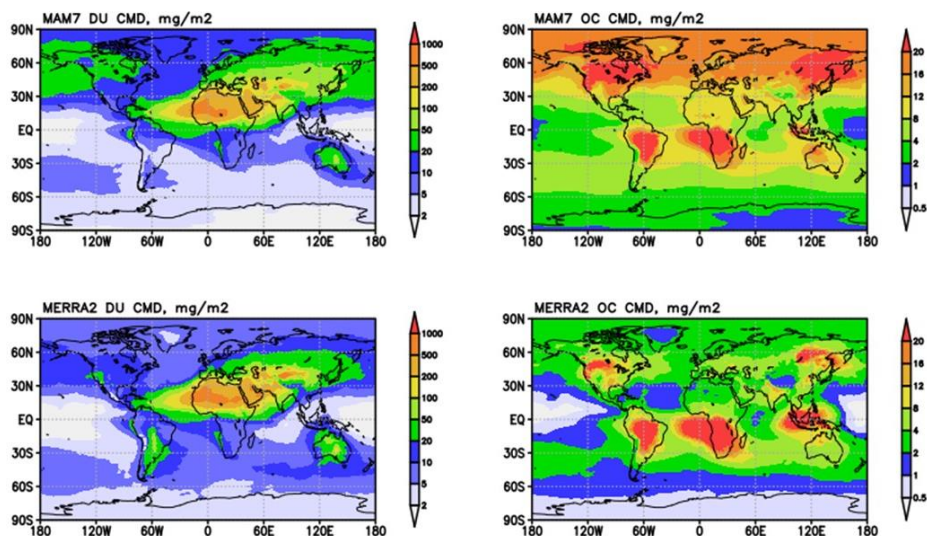


Figure 10 Column mass density for dust and organic carbon aerosols for MAM-7 (top) and MERRA2 (bottom).

MAM-7 simulated aerosols display similar spatial distribution as MERRA2 except for high-latitude region. This excessive aerosol build-up near high latitude region is also found in operational NGAC system, and

will be further investigated.

In this project, GMAO’s emissions data sets are also adopted into NEMS GSM. Dynamic sources (wind-speed dependent) are considered for DMS, dust, and sea salt. For SO₂ and carbonaceous aerosols, anthropogenic and nature emission sources are considered. Since MAM-7 is based on the same emission data sets as MERRA2, higher aerosol loading implies longer aerosol lifetime. Budget, lifetime, and partition between dry and wet removal in MAM-7 will be analyzed using our 2016 Jan-Dec simulations spanning the full annual cycle.

Aerosol optical depth (AOD) at 550 nm from MAM-7 and GOCART runs are compared with MERRA2 analysis and AEROSOL ROBOTIC NETWORK (AERONET) observations. AERONET sites do not sample AOD at 550 nm so the AOD at 550 nm is calculated by linear interpolation on a logarithmic scale from AODs at adjacent wavelengths (440 and 675 nm). Figure 11 shows AOD time series at four

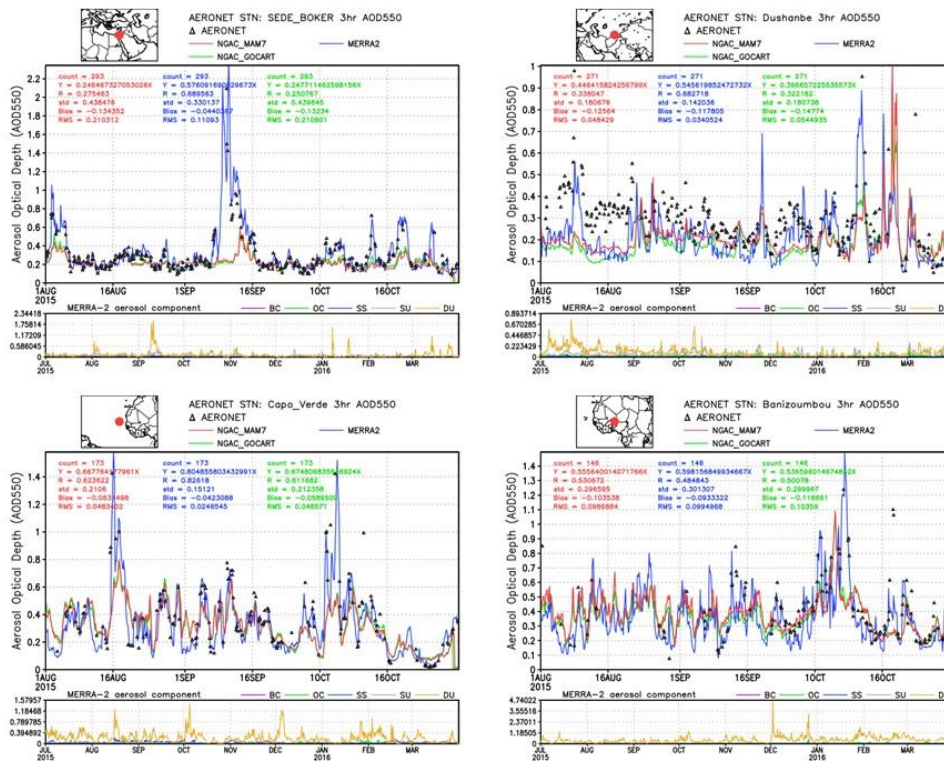


Figure 11 Time series of AOD at 550 nm from GOCART (green), MAM-7 (red), MERRA2 (blue), and AERONET observations (black) at 4 AERONET sites. The lower panel displays aerosol composition from MERRA2.

dust-dominated sites covering three dust source regions (Sede Boker in mid-east, Dushanbe in Asia, and Cape Verde and Banizoumbou in Africa). Composition information (partition among dust, sea salt, sulfate, OC, and BC) from MERRA2 is displayed as well. Statistics (e.g., mean bias, correlation, and root mean square error) between model and observations are

also calculated. Both MAM-7 and GOCART capture Africa dust storms well but fail to capture mid-Sept

dust outbreak in mid-East. For Asia, MAM-7 and GOCART simulated AOD is consistently lower than observations.

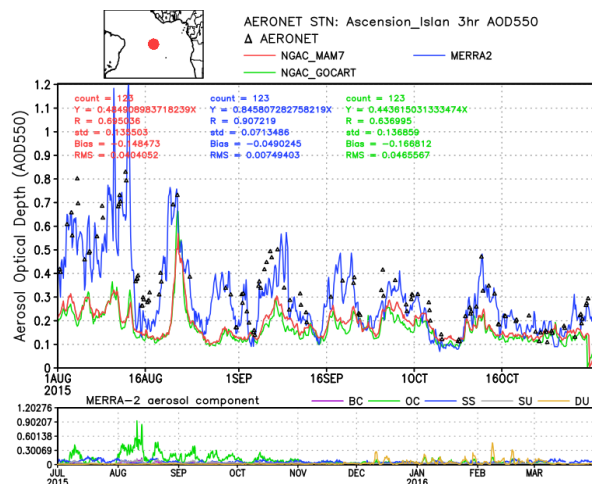


Figure 12 Time series of AOD from GOCART, MAM-7, MERRA2, and AERONET at Ascension Island.

Analysis over those sites dominated by other aerosol species is also conducted. Figure 12 shows the time series at Ascension Island. This site is located in remote southeast Atlantic, within smoke outflow region. GSFC’s smoke emissions, Quick Fire Emissions Data Version 2 (QFED2) from polar orbiting sensors (Darmenov and da Silva 2015), is used in GOCART, MAM-7, and MERRA2. Low biases in smoke aerosols are found in MAM-7 and GOCART runs despite using the same

smoke emissions as MERRA2. The discrepancy is likely attributed to the lack of data assimilation in GOCART and MAM-7 runs (Lu et al., 2017).

Figure 13 shows correlation coefficients and mean biases of MAM-7 AOD against AERONET observations for the 3-month period. These global maps provide valuable insight in overall model performance. Same as time series analysis presented above, the evaluation efforts have been focused on these regions dominated by specific aerosol species (i.e., dust-, sulfate-, seasalt-, and smoke-dominated). For instance, negative biases are found in south America, south Africa, and southeast Asia where smoke aerosols are dominated. This highlights the need to revisit how smoke aerosols (in particular smoke emissions) are handled in the model.

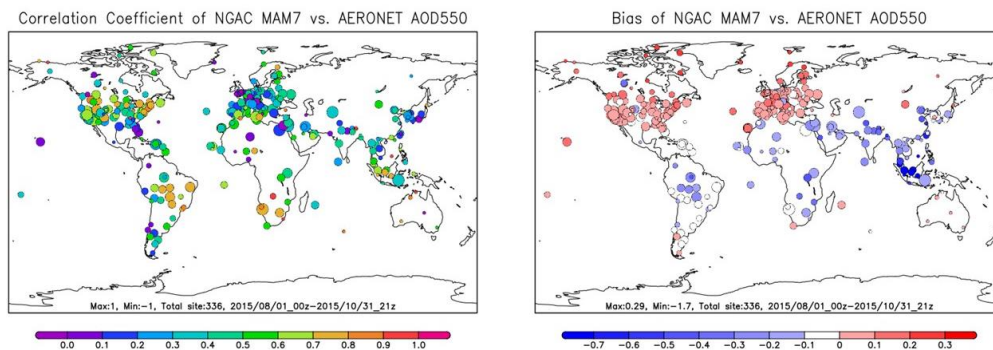


Figure 13 Global map of correlation (left) and mean bias (right) between MAM-7 and AERONET AOD.

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3. Highlights of Accomplishments

The project deliverables represent needed physics upgrade with respect to the current configuration (e.g., aerosol attenuation is determined from OPAC climatology and aerosol indirect effect is not considered). The ultimate goal is to accurately represent the aerosol processes and effectively account for aerosol effects with the available computer resources. Highlights include:

- NEMS GSM physics suite is upgraded. GMAO’s physically-based aerosol and cloud microphysics package (MAM-7 aerosol scheme; MG cloud microphysics; and CCN/IN activation) are implemented, tested and evaluated in NEMS GSM.
- NEMS GSM is restructured to couple with GEOS-Chem. The infrastructure allows NEMS GSM invoke either GOCART or MAM-7, and can be easily extended to run other chemistry modules within GEOS-Chem.
- A poster on “Investigation of aerosol-cloud interaction using NCEP global models” was presented at AMS annual meeting, Seattle, 22-26 January, 2017 and an oral presentation on “Investigation of aerosol-cloud Interaction for extreme precipitation events using NCEP global models” was given at AOGS 14th annual meeting, Singapore, 6-11 August 2017.

4. Transitions to Applications

Project transition plan were submitted to and reviewed by the NCEP management team, including:

- The transition plan was submitted to the CTB director and discussed at a CTB side meeting at the NOAA Climate Diagnostics and Prediction workshop, Oct 20-23, 2014

- Presentation of operational deployment plan was presented by the EMC PI at quarterly R2O meeting at NCEP, March 20, 2015

This project seeks to facilitate the R2O transition by managing the code development using NCEP SubVersion (SVN) code repository and performing the work under quasi-operational environment, using parallel run scripts. The SVN approach allows our code changes to be transparent to other NEMS developers, and thus facilitates coordinated development so all or part of our physics changes can be tested together with other physics upgrades that are being developed at EMC and/or by external research community.

After extensive test, NOAA has chosen FV3 as the dynamic core for Next Generation Global Prediction System (NGGPS) in summer 2016. A major effort is undertaken at NCEP to unify many of EMC's currently independent atmospheric models under the FV3 dynamic core, and evolve NGGPS toward a fully-coupled Earth system model for global and regional applications. As EMC modeling suite is migrated toward a FV3-based unified system, NEMS GSM development work has been suspended.

As discussed earlier, GMAO adopts fine-grained system design in GEOS-5 while NCEP takes a coarse-grained approach in NEMS. The MG scheme has been implemented into NEMS GSM physics suite after removing all ESMF code. In contrast, ESMF-based approach is used to bring MAM-7 into NEMS GSM where NCEP_Chem component, containing MAM-7, is created and then coupled with NEMS GSM using ESMF couplers.

The prototype NGGPS system has been developed by coupling FV3 dynamic core with GFS unified physics suite (the same physics suite in NEM GSM) under the NEMS framework. During the FV3-GFS development, ESMF coupler linking physics and chemistry have been stripped away. Since MG is implemented into the unified physics suite, it is automatically migrated to FV3-GFS. On the other hand, ESMF-based chemistry coupling architecture is not available to couple FV3-GFS with ESMF-based chemistry components.

Challenges on time lines – Migration to FV3

The NCEP_Chem (containing newer GOCART, MAM-7, and AChem) is not being transitioned back to EMC repository because: (1) NEMS GSM code has been frozen, and (2) FV3-GFS lacks ESMF-based coupling architecture for bringing in ESMF-based chemistry components. The project ends in July 2017 when the decision on the chemistry coupling strategy (Fortran-based parametrization level versus ESMF-based component) is being actively discussed by NCEP Strategic Implementation Plan (SIP) Aerosol and Atmospheric Composition working group. The NCEP_Chem transition can't proceed until the coupling strategy is recommended by SIP working group and accepted by NCEP. It is inevitably a post-project effort.

Challenges on time lines – HPC request

The submitted proposal requested an account at NOAA HPC (gaea cluster) for development work. The scientist full-time tasked for the project is a foreign national. The request to obtain an account at gaea has been pending throughout the funded project, effectively being denied. The NEMS GSM source code and related scripts were first ported to SUNYA cluster, and later to NESDIS-funded Supercomputer for Satellite Simulations and Data Assimilation Studies (S4). The S4 cluster provides operational-like environment with access to NCEP SVN code repository, and is the primary platform for code development and experiments in this project. The lengthy wait and unsuccessful attempt to obtain a NOAA HPS account is a major drag.

5. Publication from the Project

Two manuscripts are in preparation. One manuscript is to describe the implementation of MAM-7 into NEMS GSM, and compare the aerosol simulations from GOCART versus MAM-7 for the 2016/01-2016/12 period. The other manuscript is to conduct NEMS GSM experiments for investigating aerosol-cloud interaction for various scenarios.

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