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Generalized Aerosol/Chemistry Interface (GIANT)

A Community Effort to Advance Collaborative Science across Weather and Climate Models

Alma Hodzic, Natalie Mahowald, Matthew Dawson, Jeffrey Johnson,
Ligia Bernardet, Peter A. Bosler, Jerome D. Fast, Laura Fierce, Xiaohong Liu,
Po-Lun Ma, Benjamin Murphy, Nicole Riemer, and Michael Schulz

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ABSTRACT: Atmospheric aerosol and chemistry modules are key elements in Earth system models (ESMs), as they predict air pollutant concentrations and properties that can impact human health, weather, and climate. The current uncertainty in climate projections is partly due to the inaccurate representation of aerosol direct and indirect forcing. Aerosol/chemistry parameterizations used within ESMs and other atmospheric models span large structural and parameter uncertainties that are difficult to assess independently of their host models. Moreover, there is a strong need for a standardized interface between aerosol/chemistry modules and the host model to facilitate portability of aerosol/chemistry parameterizations from one model to another, allowing not only a comparison between different parameterizations within the same modeling framework, but also quantifying the impact of different model frameworks on aerosol/chemistry predictions. To address this need, we have initiated a new community effort to coordinate the construction of a Generalized Aerosol/Chemistry Interface (GIANT) for use across weather and climate models. We aim to organize a series of community workshops and hackathons to design and build GIANT, which will serve as the interface between a range of aerosol/chemistry modules and the physics and dynamics components of atmospheric host models. GIANT will leverage ongoing efforts at the U.S. modeling centers focused on building next-generation ESMs and the international AeroCom initiative to implement this common aerosol/chemistry interface. GIANT will create transformative opportunities for scientists and students to conduct innovative research to better characterize structural and parametric uncertainties in aerosol/chemistry modules, and to develop a common set of aerosol/chemistry parameterizations.

SIGNIFICANCE STATEMENT: Accurate predictions of atmospheric aerosols and trace gases concentrations in current and future atmosphere are key to determining their effects on human health, weather, and climate. Atmospheric scientists and students currently face major difficulties in developing, maintaining, and using state-of-the-art aerosol and chemistry numerical parameterizations within increasingly complex Earth system models. This article describes the ongoing effort of the Earth system modeling community to build a Generalized Aerosol/Chemistry Interface (GIANT) that will facilitate the use and improve the accuracy of aerosol and chemistry representations within current air quality, weather, and climate models.

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AFFILIATIONS: Hodzic and Dawson—National Center for Atmospheric Research, Boulder, Colorado; **Mahowald**—Department of Earth and Atmospheric Sciences, Atkinson Center for a Sustainable Future, Cornell University, Ithaca, New York; **Johnson**—Cohere Consulting LLC, Seattle, Washington; **Bernardet**—NOAA Global Systems Laboratory and Developmental Testbed Center, Boulder, Colorado; **Bosler**—Center for Computing Research, Sandia National Laboratories, Albuquerque, New Mexico; **Fast, Fierce, and Ma**—Atmospheric Sciences and Global Change Division, Pacific Northwest National Laboratory, Richland, Washington; **Liu**—Department of Atmospheric Sciences, Texas A&M University, College Station, Texas; **Murphy**—Center for Environmental Measurement and Modeling, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina; **Riemer**—Department of Atmospheric Sciences, University of Illinois Urbana–Champaign, Urbana, Illinois; **Schulz**—Norwegian Meteorological Institute, Oslo, Norway

The importance of feedbacks of atmospheric composition with weather and climate has been emphasized by numerous observational and modeling studies, ranging from local estimates of wildfires' effects on precipitation, to global studies assessing the benefits of emission control on air quality and climate (e.g., Shindell et al. 2012; Smith and Bond 2014; Hodzic and Duvel 2018; Touma et al. 2022). Trace gases and aerosols have been intensely studied in the past two decades as they can directly alter radiative forcing by scattering and absorbing radiation, or indirectly alter cloud formation by increasing droplet number concentrations. Unfortunately, large uncertainties still exist across different models in terms of the magnitude, sign, and future projections of radiative forcing (Shindell et al. 2013; Forster 2016; Seinfeld et al. 2016; Carslaw et al. 2018; Smith et al. 2020). Aerosols also have impacts on public health, as suggested by studies combining health data with atmospheric models and measurements (Burnett et al. 2018; U.S. EPA 2019; Pye et al. 2021). Southerland et al. (2022) found that approximately 2.5 billion people live in urban areas exceeding the World Health Organization guideline for annual average $PM_{2.5}$, leading to potentially 1.8 million excess deaths in 2019. Understanding the complex chemical and meteorological feedbacks that determine the concentration, size, and composition of particles is a key need for public health and air quality management entities.

The representation of aerosol/chemistry interactions with physics/dynamics remains one of the poorly constrained parts of current ESMs. It is unclear what fraction of these uncertainties can be attributed to structural uncertainties, lack of scientific understanding of key processes, poor constraints on model parameters, and differences in the host atmospheric model itself (Liu et al. 2012; Bond et al. 2013; Acosta Navarro et al. 2017; Fanourgakis et al. 2019; Gliß et al. 2021). The fundamental equations and properties that need to be simulated are often similar across models, but their implementation spans many structural differences arising from development choices that balance accuracy with computational resource availability. For example, for describing aerosol size distribution some models use sectional representations that track particles in different size bins (Bessagnet et al. 2004; Bauer et al. 2013), while others implement modal aerosol schemes (Liu et al. 2012, 2016; Wang et al. 2020). For chemistry, models can use different simplifications in representing oxidants, secondary aerosol formation, aqueous-phase chemistry, hydrocarbon and nitrogen oxidation cascades, heterogeneous reactions (Lamarque et al. 2012; Hodzic et al. 2020). This makes multimodel intercomparison projects challenging to design, and their results difficult to interpret. Tsigaridis et al. (2014) compared organic aerosol distributions from 31 global chemistry models within the Aerosol Comparisons between Observations and Models (AeroCom; Schulz et al. 2006) project and showed one order of magnitude divergence between model predictions near the surface (important for air pollution studies), and two orders of magnitude in the free troposphere (which is of relevance to climate studies). In principle these models attempt to simulate the same processes, but because of the differences in their implementation by different groups, comparing or contrasting aerosol schemes independent of the host model physics/dynamics is difficult. Donahue and Caldwell (2018) showed that significant differences in climate predictions can also arise from the order in which parameterizations are called within a host model that uses sequential splitting.

The aerosol modeling testbed proposed by Fast et al. (2011) was one of the first initiatives designed to facilitate the intercomparison of aerosol parameterizations and their evaluation with observations. The AeroCom (Schulz et al. 2006) and AerChemMIP (Collins et al. 2017) global models projects, the AQMEII (Air Quality Model Evaluation International Initiative) regional models project (Im et al. 2015), each represent a set of experiments and comparisons that have illuminated much about the performance of aerosol–chemistry simulations, but could be improved upon by making these comparisons routine and process-level by creating new frameworks for model–data comparison diagnostics.

In addition, the growing complexity of aerosol/chemistry parameterizations and their implementation in ESMs, can inhibit users who have just entered our field, such as graduate students at universities, from testing new parameterizations in various models, and from interacting with weather/climate modeling groups at national laboratories. Previous attempts to provide a modular framework with interchangeable aerosol/chemistry modules with a host dynamical core and several physics packages, such as Weather Research and Forecasting with Chemistry (WRF-Chem; Grell et al. 2005) and Modular Earth Submodel System (MESSy; Jöckel et al. 2005), showed the great appeal for scientists to use such tools. However, WRF-Chem ran its course due to outdated software infrastructure, its dependence on a specific dynamical core, and a lack of standardized interfaces limiting the use of aerosol/chemistry packages to a restrained number of physics parameterizations. To develop next-generation Earth system models (ESMs) suitable for addressing science challenges across multiple scales, the software infrastructure needs to be redesigned to be computationally efficient and flexible. These efforts are currently being undertaken at several U.S. institutions with the development of next-generation multiscale models such as the MUSICA (Multi-Scale Infrastructure for Chemistry and Aerosols) framework sponsored by NSF (Pfister et al. 2020), or the EAGLES (Enabling Aerosol–Cloud Interactions at Global Convection-Permitting Scales) project sponsored by DOE (https://climatemodeling.science.energy.gov/projects/enabling-aerosol-cloud-interactions-global-convection-permitting-scales-eagles). Therefore, there is a great opportunity to coordinate efforts so that future aerosol/chemistry modeling efforts are based on a common software framework.

This paper describes a new community effort aimed at developing a Generalized Aerosol/Chemistry Interface (GIANT) for use across community weather and climate models. We intend to design the architecture and requirements with rigorously defined standards by which aerosol and chemistry modules are interacting with the host atmosphere model to remove many of the shortcomings mentioned above. We plan to review the existing platforms for standards development. There is an opportunity now for the community to leverage the ongoing work to develop such an interface that will connect several state-of-the-art climate and weather models with a library of cutting-edge aerosol modules. We intend to define a set of unit and science tests to ensure both the code performance and scientific evaluation of the ensemble. This effort will transform the type of scientific experiments which can be conducted with atmospheric models, allowing a more robust identification of the sources of errors, as well as more complete comparison between parameterizations and with available observations. In addition, it will streamline the inclusion of machine learning–based processes, and new architectures into atmospheric models. Our vision is that GIANT will help coordinate different modeling groups' efforts and not replace these efforts.

As the first step, a virtual GIANT Workshop was held on 16 February 2022, to discuss interest and ways to build a next-generation platform facilitating increased interoperability of aerosol/chemistry code and collaborative research. The 76 workshop participants represented many U.S. universities, U.S. laboratories, and international institutions. The participants discussed the requirements for an interface that facilitated communication between specific aerosol–chemistry-related processes and the host model, including aerosols interface with gas-phase and aqueous chemistry, radiation, cloud microphysics, anthropogenic and natural emissions, dry and wet deposition, data assimilation, and diagnostics. The workshop was followed by the first virtual and asynchronous GIANT hackathon on 29 April–20 May and a session at the AeroCom meeting in 11–13 October 2022. The hackathon allowed us to test some of the innovative approaches and ideas that emerged from the workshop discussions. We plan to use future hackathons to ensure that the design and implementation of GIANT remains focused on addressing the needs of the community. We will provide regular updates to the community as requirements are gathered and the design of GIANT advances through the hackathons and other avenues we develop for community engagement. In this paper we present the results from these efforts and propose a path forward.

GIANT framework: Participating modeling efforts

GIANT is a collaborative effort between several global and regional aerosol/chemistry modeling groups. It will leverage past and ongoing community efforts in terms of aerosol-process model and multiscale model developments. GIANT is designed as an interface that can be implemented within host models, allowing each host model to facilitate the integration of aerosol/chemistry modules in a standardized manner. Participating host models and their ongoing development efforts are described below. Figure 1 shows in an exemplary way the

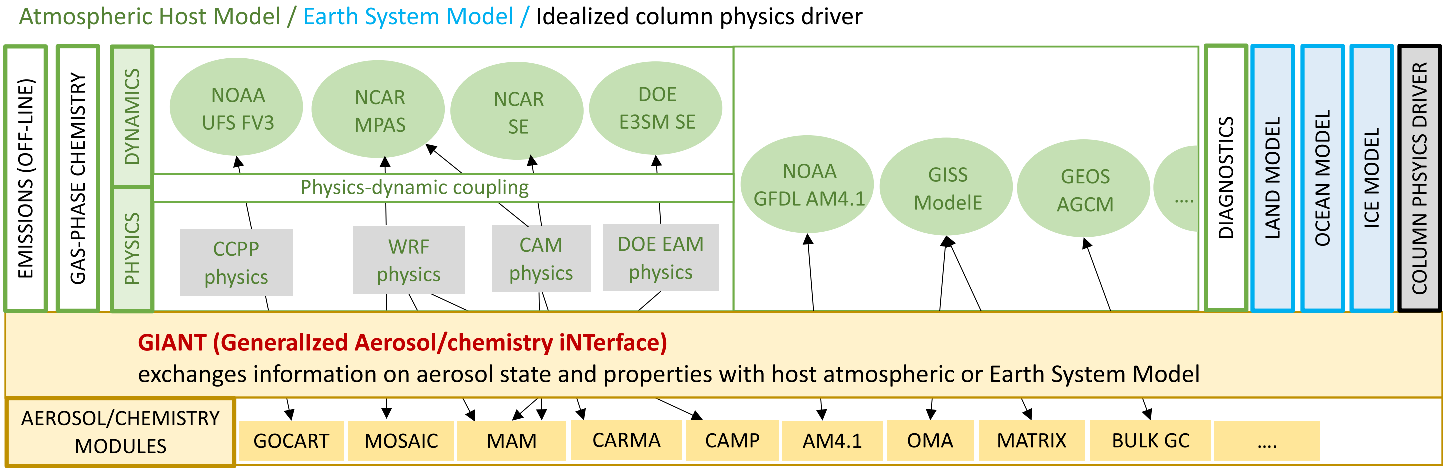

Fig. 1. **GIANT is a common interface allowing the exchange of information on aerosol state and properties between any host model (atmospheric model, Earth system model, or idealized driver) and any aerosol package. GIANT will leverage several ongoing community efforts such as MUSICA, which is aimed at coupling CAM physics driven by the SE, MPAS, or FV3 dynamical cores with CARMA and MAM aerosol packages, or EAGLES which is focused on coupling the improved MAM with the next generation E3SM written largely in C++ for exascale performance of convection-permitting simulations. As illustrated here, this effort will increase the portability of aerosol modules between community models. Aerosol chemistry modules contain aerosol processes such as coagulation, gas-particle partitioning, new particle formation, aerosol and cloud chemistry, aerosol optical properties, etc. Additional host models and aerosol chemistry modules are expected to join this effort in the future.**

diversity of aerosol packages and host models used by participants. The list of models shown in Table 1 is meant as an illustration of the diversity of the frameworks and groups which indicated interest to participate. More modeling groups have shown interest in joining and have been participating in the workshops.

Workshop results: Defining interactions between aerosol/chemistry processes and the host model

The aim of the inaugural GIANT workshop was to start conversations and identify the most pressing issues facing the aerosol modeling research community as represented by participants. At the February 2022 GIANT workshop, participants identified up to 12 specific interactions that typically occur between the aerosol packages and the host model as illustrated in Fig. 2, and discussed the requirements needed to develop this interface. Participants worked within several breakout groups based on interest in

Table 1. List of participating host and/or aerosol/chemistry models. A more detailed description of participating models is provided in the supplemental material. CAMP and MOSAIC are stand-alone aerosol/chemistry treatments.

Model	A brief description of the aerosol/chemistry treatment	Aerosol representation	References
CAMP	Flexible gas- and aerosol-phase chemical module that allows users to build and solve customized multiphase mechanisms at runtime.	Sectional Modal Particle-resolved	Dawson et al. (2022)
MOSAIC	Detailed aerosol process module that treats major inorganic and organic aerosol species and related processes. It is used within WRF.	Sectional Modal Particle-resolved	Zaveri et al. (2008, 2014)
GEOS-Chem	A grid-independent chemistry model that treats gas and aerosol-phase chemistry in the troposphere and stratosphere. It has been coupled with GEOS ESM, WRF, CESM, and MUSICA (work in progress).	Bulk	Hu et al. (2018), Lin et al. (2020), http://www.geos-chem.org
GISS ModelE	Includes OMA and MATRIX aerosol schemes coupled to tropospheric and stratospheric gas-phase chemistry, and aerosol processes and cloud microphysics.	Sectional Modal	Bauer et al. (2013, 2020)
GFDL AM4.1	Atmospheric component of the GFDL-ESM4 Earth system model that includes interactive tropospheric and stratospheric gas and aerosol chemistry and related processes.	Bulk	Horowitz et al. (2020)
CMAQ	Includes modal aerosol module AE7 and Community Regional Atmospheric Chemistry Multiphase Mechanism (CRACMM) coupled with several tropospheric gas-phase mechanisms Carbon-Bond-6, SAPRC07, RACM2. CMAQ is also available online within the WRF, MPAS and UFS host models.	Modal	https://github.com/USEPA/CMAQ
UFS	In NOAA's operations, uses GOCART bulk aerosol modules in one member of the Global Ensemble Forecast System (GEFS-aerosol). Research configurations additionally use CMAQ and simplified configurations with smoke and dust as tracers that interact with meteorology.	Bulk Modal	Jacobs (2021)
MUSICA	Includes MOZART gas-phase chemistry and MAM4 and CARMA aerosol modules.	Sectional Modal	Pfister et al. (2020)
E3SM	Includes aerosol parameterizations based on MAM4 with improvements related to aerosol treatment in clouds.	Modal	Rasch et al. (2019), Golaz et al. (2019), Wang et al. (2020)

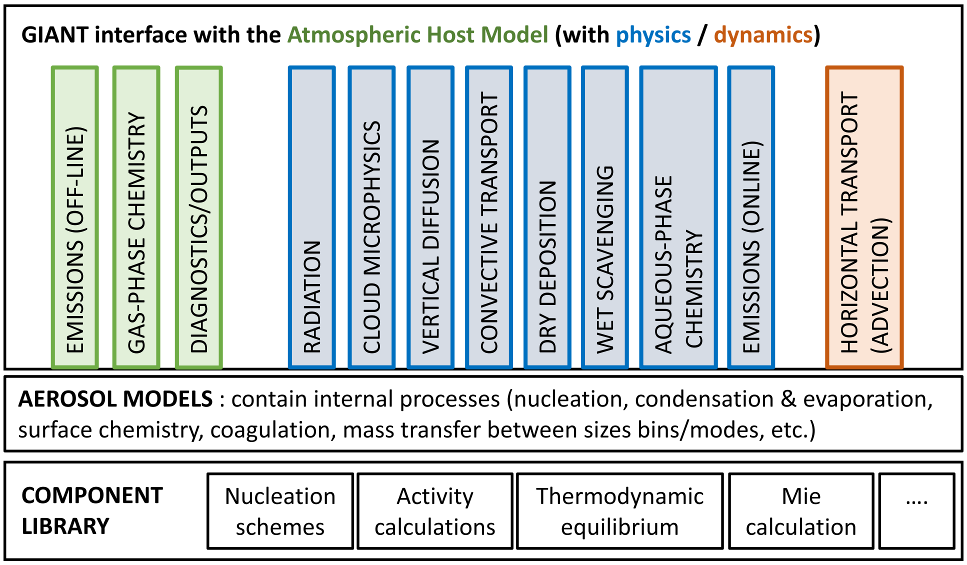

Fig. 2. Schematic representation of an interface that allows a given aerosol package/model to interact with the rest of the host model.

different areas of aerosol modeling. Each group held a facilitated discussion, the essential points of which are reported below. The follow-up discussions were organized within the October 2022 AeroCom community workshop.

Aerosol internal processes (microphysics, thermodynamics, secondary organic chemistry, growth, and aging). The processes that govern the formation, growth, and evolution of aerosols are tightly coupled with the way that aerosol size distributions and mixing state are represented in each model. In many cases, the size distribution determines the set of processes that can be represented in the aerosol life cycle. Aerosol mixing state (e.g., externally or internally mixed populations) refers to the distribution of chemicals within a particle population, and plays a key role in determining aerosol properties [e.g., optical properties, hygroscopicity, cloud condensation nuclei (CCN), and ice nuclei (IN) activity]. Consequently, creating a single programming interface that accommodates diverse aerosol size representations (e.g., bulk, modal, sectional, and particle-resolved) and mixing state assumptions is challenging. This challenge arises from the approach traditionally used to incorporate aerosol packages within Earth system and weather prediction models. Typically, aerosol modules have been added into an atmospheric host model wherever needed without a well-defined interface that delineates the aerosol package. Additionally, during the initial implementation, decisions were made regarding the sequence in which physico-chemical processes were performed and how their effects were incorporated, making it difficult to analyze and experiment with alternative decisions. This difficulty can be largely addressed by an approach that separates the aerosol package from the host model, which is one of the aims of the GIANT collaboration.

Aerosol interface with gas- and aqueous-phase chemistry. Creating a general model-independent interface for gas- and aqueous-phase chemistry interactions within the physical model is challenging as some aerosol/chemistry models only include a limited set of reactions (e.g., sulfur dioxide to sulfate), while others include a near-explicit treatment of aqueous-phase constituents. In addition, coupling aqueous-phase reactions and cloud processing requires coordination with cloud physics (see section "Aerosol interface with cloud microphysics"). For example, accurate simulation of fast reactions such as H_2O_2 formation in gas/aqueous phase, requires adequate time stepping in the chemistry solver. The chemistry is influenced by photolysis rates, thus requiring feedback from radiation changes by clouds and aerosols. Many models include separate tropospheric and stratospheric chemistry mechanisms requiring that both be integrated into this framework. Different models employ different time stepping methods for chemistry, which would need to be accommodated. Participants stressed that software choices should not limit scientific exploration, but rather the interface should be designed to facilitate addressing a range of science questions. Several ideas were proposed to address these challenges. GIANT should support scalable aerosol complexity, which may require that the gas/aqueous chemistry be solved together with the cloud microphysics and the wet removal processes. Generalizing the configuration and input files for all gas-/aqueous-phase chemistry solvers would enable exchangeability of chemical systems. Enabling dynamic configuration of the number of advected species and simulated reactions could further enhance flexibility.

Aerosol interface with radiation. Aerosols interact with radiation, causing changes in the energy balance, and calculations of aerosol direct radiative impact are extremely important results from the aerosol scheme. Generalizing this element has potential to be both important, and yet perhaps more straightforward than other elements in this effort. Aerosol interactions with radiation are wavelength dependent and can be computationally expensive. Usually, a separate optics module is called to compute aerosol optical properties over the required wavelength bands using inputs from the aerosol module on aerosol concentrations, composition, and properties, including how much they have grown due to humidity. The optics module thus needs to know what type of aerosol framework is being used, assumptions about size and composition, as well as aerosol optics. Note that the host model will determine the required wavelength bands, so the interface needs to be flexible to pass information of different wavelength bands, as well as aerosol state (i.e., aerosol types, sizes, mixing states). Often the relationship between aerosol state with the optics is stored in a large lookup table resulting from computationally expensive calculations. Building and maintaining this lookup table for different optics models and aerosol representations will need to be done in a way that allows for careful checking of assumptions.

Aerosol interface with cloud microphysics. Creating an interface for aerosol interactions with cloud microphysics may be one of the most difficult tasks in the GIANT effort due to the structural heterogeneity in both aerosol representations and cloud microphysics, and the tight coupling between the two. There needs to be a two-way interaction between aerosols and clouds, as clouds modify aerosols and vice versa. Some participants argued that the aerosols and microphysical parameterizations for clouds should not be generalized because of their tight interconnection. On the other hand, aerosol–cloud interactions are some of the most important for climate impacts, as well as the removal of aerosols from the atmosphere, which argues that including this process in any generalized framework is key. There are many questions about how to do this in a general manner. The first issue is how to deal with the different levels of complexity: for example, some models track the aerosol component within cloud droplets, some include aerosol processing within clouds, and others do not include these processes. Second, many of these processes important to microphysics models (scavenging, resuspension) are intimately connected to aerosol processes discussed in other sections (coagulation, aqueous chemistry). Other processes that are critical for the formation of aerosol activation rates as cloud condensation nuclei include cloud processing and subsequent resuspension. Finally, certain microphysical schemes may only work with specific aerosol specifications.

Aerosol interface with emissions and deposition for biogeochemistry and snow/albedo. Some Earth system models include in their calculations of biogeochemistry the new inputs from atmospheric deposition of atmospheric nutrients and pollutants (e.g., Tagliabue et al. 2014).

In addition, aerosol deposition onto snow and ice has been shown to be potentially important for climate and hydrology and is included in many models (Hansen and Nazarenko 2004; Flanner et al. 2009). Thus, linking the aerosol deposition calculated in the atmosphere to the processes on land, ocean, or sea ice can be important. Since many of these processes are not part of the atmospheric model itself, this will require working with elements of the other components of the ESM. The parameters that would be passed are deposition fluxes of dust, black carbon or other absorbing aerosols, Fe, P, and N, although other elements or components could be important. The temporal evolution of the dry and wet deposition fluxes may need to be included, so linking the deposition should be done at hourly scales, but is only needed for the surface flux of the model. Dust emission schemes have been put into land or atmospheric components of ESMs, and such differences may complicate the definition of a default GIANT interface.

Similar information should be available for both bulk and modal schemes. One of the biggest issues will be dealing with different levels of complexity. Some models will not include detailed speciation, so parameterizations that could convert simpler schemes into more detailed nutrient distributions will need to be developed.

Aerosol interface with dry deposition and wet scavenging. Dry deposition and wet scavenging are primary mechanisms for aerosol removal, and large-scale models incorporate algorithms representing these processes to varying degrees (Hogrefe et al. 2018). They operate on different temporal and spatial scales, responding to diverse meteorological, chemical, and surface drivers. Relative humidity is a key parameter needed to calculate the particle size after water uptake. Future large-scale models may resolve dry deposition to tall canopies (e.g., forests, cities). Wet scavenging occurs in-cloud or below-cloud and is one of many aerosol–cloud interactions that must be resolved for proper treatment of the aerosol budget and the impact of aerosols on meteorology. Many large-scale models include dependence on particle size and composition when calculating particle losses in response to cloud formation and rain events. Once particles are collected by hydrometeors, some models immediately remove them from the atmosphere, while others allow them to persist to the end of the model time step and regenerate after hydrometeor evaporation. Models with coupled meteorology and chemistry allow concentrations of pollutants to persist within hydrometeors to future time steps and explicitly model their transport, regeneration, or deposition. To support the present model ecosystem, GIANT will need to facilitate both calculation of loss tendencies and transfer of pollutant concentrations among multiple phases.

Aerosol interface with transport and vertical mixing. Typically, there is a clear separation between tracer transport and aerosol/chemistry modules, with distinct subroutines treating these functionalities in the code. Resolved horizontal and vertical transport is handled through advection by the dynamical core of the atmospheric component of the Earth system model. In cases where advective processes are not resolved, e.g., simple drivers and single-column models, advection is prescribed. Unresolved transport, occurring at smaller spatial scales than those explicitly represented by the dynamical core, is usually represented using a combination of diffusive algorithms, explicit diffusion, and mixing represented via physical parameterizations. The latter, while mostly important in the planetary boundary layer (PBL) and often represented using one-dimensional column PBL parameterizations, can be active in the entire vertical model column and sometimes includes three-dimensional processes. The GIANT interface will need to provide two-way communication of the model state, including relevant tracers, between the host model and the aerosol/chemistry modules. The spatial and temporal frequency of exchange should be flexible to allow for less frequent or lower-resolution computation of aerosol/chemistry processes compared to dynamical processes. Another consideration is input/output (I/O) processes, and GIANT will establish guidelines regarding the ability of aerosol/chemistry modules to import/export data or whether all communications will flow through the host.

Aerosol and chemistry diagnostics, forecasts, and data assimilation. Improving air quality modeling and forecasts is crucial to prevent the millions of annual deaths caused by poor air quality. Because of the increase in satellite and ground based remote sensing, and in situ observations, there are substantial data that can be used to enhance model performance and data assimilation. Creating an interface that facilities comparisons with observations and improvements in models from data assimilation is essential. However, this task is complex due to several factors. Different data sources operate on various temporal and spatial scales, covering different time periods. Forecasting air quality requires imputing meteorology, emissions, and aerosol/chemistry data for a specific time period and simulating forward. Creating the initial condition and emissions (of wildfires or dust) for forecasts present significant challenges that require separate development. Prognostic variables in models often differ from directly observed quantities, such as total aerosol optical depth or column-integrated ozone, necessitating additional calculations. GIANT must develop robust methods to generate diagnostic variables that can be compared to observations from chemistry and aerosol models of various complexity. Ensuring the precision of diagnostic outputs while creating a generalizable interface for comparison to observations or assimilation is of utmost importance.

Follow-up meeting during AeroCom. The follow-up GIANT community meeting was held 10–14 October 2022 during the AeroCom workshop that took place in Oslo. The meeting sought to engage the European aerosol modeling community in the effort of building a common interface within the GIANT project. Participants reviewed the existing solutions that have been used to couple aerosol modules within weather and climate host models in Europe such as the ongoing efforts to build a model-independent aerosols/chemistry component within global aerosol–climate models such as ECHAM-HAM (Zhang et al. 2012) and NorESM (the Norwegian Earth System Model).

Furthermore, the group discussed the differences in approaches that have been adopted in the development of next-generation multiscale models such as NCAR MUSICA and DOE Energy Exascale Earth System Model (E3SM; Fig. 3). NCAR is taking an approach to building a model-independent interface to aerosol packages that involves refactoring each of the ~15 parts of the CESM model that interact with aerosol modules. This interface will initially allow CESM to communicate with the Modal Aerosol Module (MAM) and Community Aerosol and Radiation Model for Atmospheres (CARMA) packages. The structure of the interface centers around a state-dependent (prognostic) and a state-independent (properties) abstract class, which can be extended by specific aerosol packages to communicate with the host model. Concurrently, the DOE is developing HAERO (High-Performance Aerosol Package Interface, http://github.com/eagles-project/haero) to facilitate communication between the host E3SM's Atmosphere Model (EAM) and the MAM aerosol package. HAERO defines an aerosol package as an aerosol configuration describing a particle size distribution and data structures for prognostic and diagnostic variables, and a set of aerosol processes (functions) that produce tendencies for prognostic variables. The host model has the responsibility for assembling and integrating aerosol processes into a solver for aerosols. Although these products are being developed to meet different, specific needs, structural and conceptual similarities exist between the approaches. The hope is that the participation of both these teams in the GIANT project, alongside other institutions addressing similar issues, will lead to frequent discussions of challenges encountered, lessons learned, and successful design strategies. These interactions will benefit the individual efforts and are expected to lead

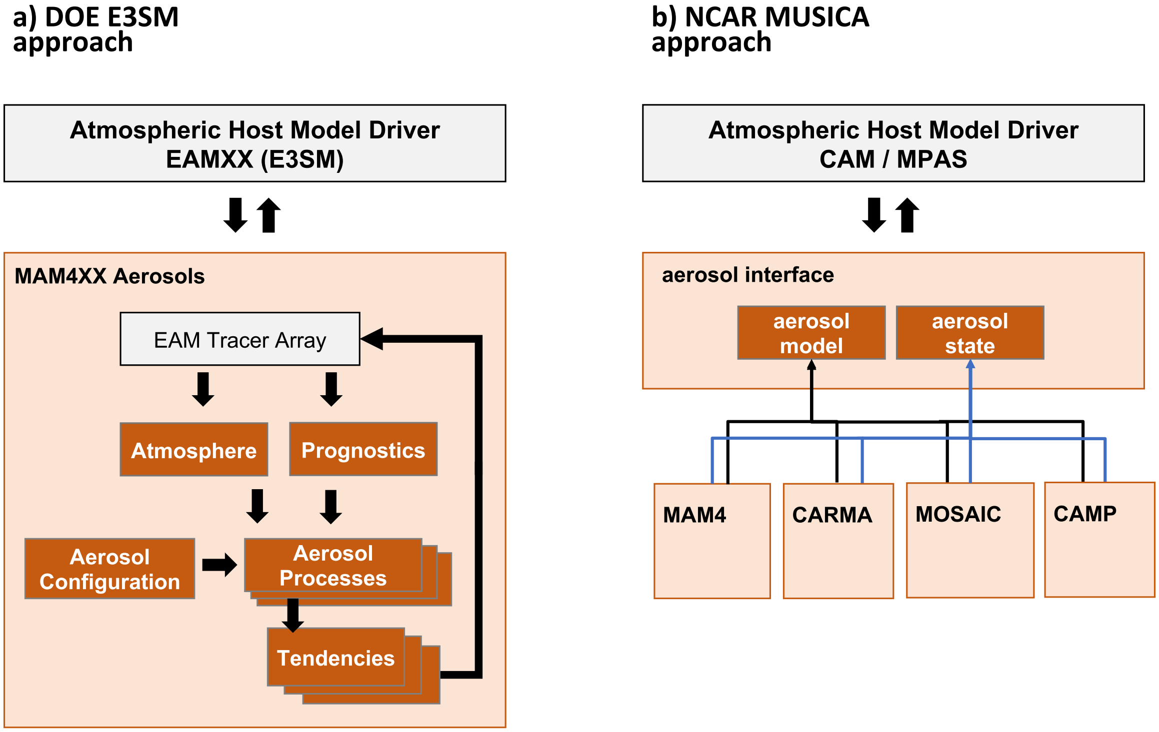

Fig. 3. Coupling approaches as currently being implemented in the DOE E3SM and NCAR MUSICA models.

to the gradual development of a common strategy for intercomparison of aerosol packages that will be the primary outcome of the GIANT effort.

Participants confirmed their interest and need for (i) building aerosol packages that are free of external dependencies and can be built as standalone software libraries, (ii) a well-defined and documented community interface between aerosol modules and host models specifying what aerosol modules need from the host model, and (iii) standards for unit and science testing to provide both portable and robust aerosol code. The group agreed that GIANT should invite the community to submit their ideas for designing a set of science tests for benchmarking individual aerosol processes that can be used in the community for all future aerosol model development.

Building GIANT components: Hackathons

Infrastructure requirements. The goal of this effort is to develop an abstract interface for aerosol microphysics and chemistry that places as few scientific and structural constraints as possible on both the aerosol packages that implement it and the host models that use these packages. This is nontrivial, as evidenced by the lack of such a generalized interface to date, but current efforts in MUSICA and EAGLES will be leveraged for this effort, making the approach much more achievable. Unlike trace gases that are characterized by only a couple of parameters (e.g., solubility and molecular weight), aerosol modules need information on a range of properties (e.g., size, chemical composition, molecular weight, hygroscopicity, optical properties). Additionally, although the proposed framework will facilitate the incorporation and evaluation of cutting-edge science, the challenge of designing this interface is primarily technical rather than scientific. It requires cocreation of the interface engaging scientists and software engineers collaboratively from the beginning to end of this process. A set of requirements for GIANT has been developed as part of the workshop (Fig. 4).

We will involve software engineers from the beginning of the design phase and define clear roles for scientists and software engineers in the design, development, and maintenance of the proposed interface. Scientists will be responsible for identifying the functionality required

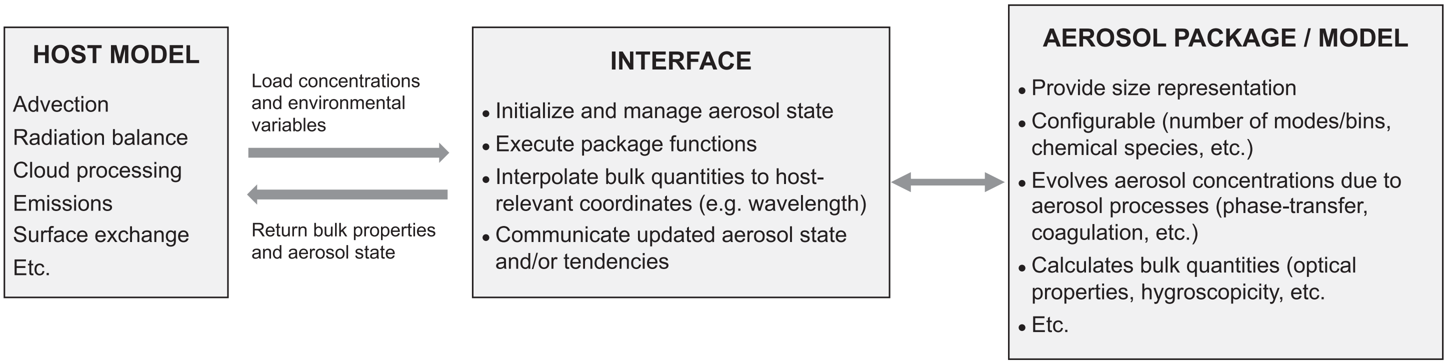

Fig. 4. Schematic representation of the typical role of an interface sitting between an aerosol package and the host model. An aerosol package typically adopts an aerosol representation (e.g., modal, bin, particle-resolved, quadrature, etc.) and includes all the properties and functions needed to calculate diagnostic bulk properties and evolve the aerosol state in time. An aerosol/host model interface contains the protocol for two-way communication between an aerosol package and the driver host model.

of a general aerosol package, ensuring that the interface will support leading-edge science. Software engineers will be responsible for the design of the interface and its implementation. This will allow the interface to benefit from modern design practices and standards to ensure the sustainability of the code base and the applicability of the interface to next-generation models. Specifically, the proposed work will facilitate the following:

(i) *Requirements-based development process*. Contemporary methods for organized development, such as the Agile method, will be implemented, from the first brainstorming session, with a commitment to a structured approach to development of the proposed interface. Two important components of the Agile method are rapid prototyping and frequent releases. This enables software engineers to try out new designs as requirements evolve and frequent releases allow these new changes to be put into use by the community.

(ii) *Standalone/generalized code*. The aerosol packages will be built as standalone libraries. This will ensure that the interface is truly generalized. Host models will interact with aerosol packages through a well-defined and documented programming interface (see Fig. 2). An aerosol package implementing the proposed interface can be built into a single library that any host model can link to with all configuration and functionality exposed through the GIANT interface.

(iii) *Improved testing*. 80% code coverage by unit tests will greatly increase the sustainability of these complex code bases, as without such tests, bugs introduced in later developments are only identifiable by dramatic failures or careful, by-hand searching. Integration tests (evaluating results from a piece of software run under prescribed conditions) will be used in combination with unit tests. Unit tests also can be used as an example of how to use each element of the programming interface, benefitting potential new users (both scientists and developers). While an interface cannot dictate the quality of the code that implements it, we commit to, at a minimum, supporting the ability of aerosol packages to apply best practices related to testing. We will also provide detailed guidelines for developing sustainable aerosol packages that include comprehensive testing suites.

(iv) *Applicability to current and next generation models*. The proposed interface will be usable by primarily procedural, build-time configured models and frameworks, as well as next-generation models applying streamlined build processes and modern design patterns.

(v) *Portability*. The Interface will support C++ and FORTRAN for efficient intralanguage transfer of information models and aerosol packages, and less efficient wrappers for interlanguage transfer of information models and aerosol packages for scientific comparison and evaluation only. To address the needs of the aerosol and chemistry modeling communities, it will be necessary for GIANT to be applicable to models that employ specific packages for coupling components within Earth system models, such as the Earth System Modeling Framework (ESMF).

(vi) *Detailed documentation and instructions can flatten the learning curve*. The most advanced and functional interface for aerosol packages is useless without clear, up-to-date instructions on its features and guidelines for its implementation. A set of standards will be developed by the software engineering team for documentation of the interface, which would allow for easier development of tutorials.

Building a prototype for aerosol/radiation interface during the first hackathon. Whereas the initial GIANT workshop used a *top-down* approach to gather ideas incorporating all aspects of the issues with portable and interoperable aerosol packages, the hackathon was a *bottom-up* effort in which participants focused on a single aspect of the aerosol/host model interface to try out some of these ideas. These two approaches complement one another and switching between them provides a change in perspective that deepens one's understanding of a problem.

For this first hackathon, the GIANT organizing committee selected a basic aerosol optics parameterization extracted from an atmospheric model at NCAR. Selecting this simple parameterization left room for addressing software and interoperability issues that pertain to all aerosol process implementations, at the expense of answering science-related questions. Participants were provided with a prototype of this interface, and with an atmospheric box-model driver to run the interface. The interface prototype was created by software engineers prior to the hackathon and implemented all the best coding practices as mentioned above, including a framework for both C++ and FORTRAN aerosol code. The code was shared with participants through GitHub and Docker containers to allow easy setup of the code and preparation of simulations. As illustrated on Fig. 4, the prototype interface was designed to handle two-way communication between an aerosol package and the driver host model. Participants were asked to implement their own aerosol model that calculates optical properties on a wavelength grid, given an aerosol state at a single point in space.

We took a few lessons from the hackathon. First, concrete issues are much easier to attack than abstract/general ones, so focusing on a single issue or tightly related set of issues is essential. Our narrowly scoped topic, the calculation of aerosol optical properties, allowed participants to obtain a result using their own aerosol packages during the hackathon. Second, we observed that participants spent an enormous amount of time installing I/O libraries and trying to get the hackathon code and their model to compile on various platforms. We anticipated this issue and offered an option for using prebuilt I/O libraries in a Docker container, and those participants that took advantage of this option surmounted this problem easily. A varying, but often significant, amount of time was also spent preparing existing aerosol module code to be usable outside of its host model of origin. This suggests that building an interface that aerosol models *can* connect to is only part of the work. Adapting existing aerosol codes so that they can function in such an environment often requires significant refactoring work.

In future hackathons, we are interested in trying a "de novo" approach to aerosol modeling, in which we state a problem to be solved that represents a set of technical challenges (e.g., translating between aerosol representations), and challenge participants to tackle it directly without involving legacy models. This would change the focus from accommodating existing models (and their complicated dependencies) to solving problems and building technical expertise. We could support this approach by preparing tools and utilities that help participants with those technical aspects of the problem we are able to anticipate.

We found that the participants responded positively to the logistics and structure of the hackathon. The hackathon took place over two weeks with a kick-off meeting, status meeting at the end of the first week, and wrap-up meeting at the conclusion of the second week. All meetings were recorded, and asynchronous communication was supported during the event with a dedicated Slack channel. Participants seemed pleased with this approach and appreciated that they could participate while meeting their existing commitments.

Above all, we realized that the conversation about interoperable aerosol models is just getting started and needs more discussion and experimentation to flesh out specific issues of interest to the community and to set priorities.

Future directions

Atmospheric scientists and students currently face many difficulties in developing, maintaining, and using state-of-the-art aerosol packages within increasingly complex Earth system models. To make progress, we propose four types of activities as described below. To manage these activities, we propose a committee of scientists and software engineers who can work together to coordinate and prioritize efforts based on feedback from stakeholders.

Organize in-person and virtual workshops. GIANT will organize a combination of in-person and virtual workshops twice a year to discuss the state of the science for each interaction of an aerosol module with other parts of an atmosphere model and review the weaknesses and strengths of the existing parameterizations. This is an opportunity for participating modeling groups to provide input on modeling tools (including call tree, passed variables, architecture) and other needs for addressing scientific challenges. These workshops can promote discussions between aerosol/chemistry scientists, software designers/programmers, and students.

Design a generalized interface to accommodate community needs. Using the information collected during the workshops, scientists and software engineers will work together iteratively to develop an associated interface that meets the needs of the community. While some architectures/approaches may not be accommodated in a common interface, GIANT will seek the best and most inclusive technical solution that accommodates as many requirements and scientific goals as possible. The goal is to facilitate the incorporation of aerosol and chemistry modules in major chemistry–climate models such as E3SM and MUSICA.

Several different processes parameterized in aerosol/chemistry modules will be addressed in this effort, including coagulation, gas-particle partitioning, new particle formation, aerosol and cloud chemistry, aerosol optical properties, dry and wet deposition, etc. Each of these parameterizations comes with their own set of challenges. For each of these aerosol modules, the appropriate variables (gas/aerosol concentrations, aerosol size, hygroscopicity, optical properties) must be passed between the host model and the aerosol/chemistry modules. For some processes, the interface will allow for communication with the other parts of the host model such as the land model (e.g., dry deposition, biological emissions) or the ocean model (e.g., sea salt emissions).

Organize additional hackathons. Hackathons will either focus on a specific interaction between aerosol modules and other science modules, or on specific technical challenges (e.g., translating between aerosol representations). We expect to organize two virtual and asynchronous hackathons each year. During the hackathon, a prototype interface for a given aerosol/host model interaction or a solution to a specific technical challenge will be developed. After the hackathon, software engineer and scientist members of GIANT will implement and evaluate the solution in the aerosol/chemistry modules and weather/climate models they maintain.

To facilitate the coupling and evaluation work resulting from hackathon prototype development, GIANT will also work on connecting the aerosol interface to single column atmospheric models that contain physical parameterizations, and provide environmental conditions to the interface. Column models such as the NCAR Single-Column Atmospheric Model (SCAM) and/or the Common Community Physics Package (CCPP) Single-Column Model models are good candidates to drive the aerosol packages and support the new interface.

Build an aerosol modeling library platform. After the proposed work has been completed, the developed interface will be hosted on GitHub along with instructions for building the interface as a software library for use in atmospheric models. Instructions will be provided to the community for using aerosol/chemistry modules that extend the common interface with compatible single-column physics models. Several single-column physics models will be adapted to serve as a host model capable of driving the chemistry/aerosol packages. This will facilitate the exchange of aerosol modules within the community and could allow nonaerosol experts to use up-to-date parameterizations while studying other aspects of the Earth system. We anticipate providing aerosol packages used at NCAR, DOE, and NASA, among others. We plan for regular quarterly releases to allow frequent feedback from the results of design, implementation, and testing of new or updated functionality. Finally, the GIANT platform will provide an environment for functional testing and benchmarking for new aerosol code before it is deployed in a 3D host model.

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Data availability statement. All the modeling platforms that are described in this manuscript have in-text references. Code that has been built during hackathons can be obtain upon request from the corresponding author. We are in the process of building a community GitHub.

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