System for Integrated Modeling of the Atmosphere (SIMA)

A Vision of a Community Atmospheric Modeling System

This document was prepared by the committee that organized the SIMA Community Workshop in 2020. Workshop participants provided feedback on an earlier draft, and a small group of participants (organizers and reviewers) provided in-depth reviews on a revised draft. We thank everyone who contributed to making this Vision Statement.

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This document lays out a vision for a unified community atmospheric modeling system inside of an Earth System Model (ESM) that allows multiple configurations for weather, climate, and geospace applications. The community was engaged to prepare this shared vision and proposed frontier science goals enabled by SIMA in a community model. Examples of frontier science topics in a range of areas (Weather, Climate, Space Weather, Air Quality) are included to illustrate how SIMA enables solutions to new research questions. This document also outlines plans for community engagement and next steps to achieve this vision. SIMA is envisioned to be a resource that is jointly designed and developed by the National Center for Atmospheric Research (NCAR) and the community. This vision was developed and refined at a community workshop in June 2020.

Overall Vision

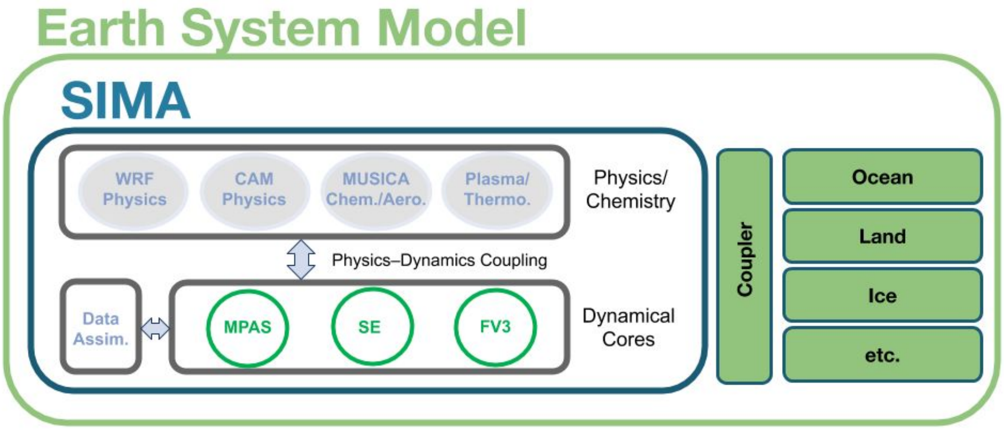
Historically, a number of highly successful atmospheric models originated with minimal similarities and specific purposes. Over the last decade, research objectives and atmospheric simulation needs have evolved and become more interconnected. As a result, atmospheric models have become more complex and models have started to share elements (but often with separate implementations and software). Increased interconnections between modeling efforts make clear that the community would greatly benefit by moving to a unified atmospheric modelling system coupled with other earth system components. SIMA is an effort to achieve this goal. There are many benefits flowing from a unified atmospheric modeling system motivating this vision:

- Frontier science goals require simulation capabilities for both existing and new applications as described in the *Frontier Science* section below.
- Atmospheric models are becoming increasingly complex, and sharing dynamical cores, parameterization packages, and infrastructure will make much more efficient use of development, maintenance and support resources, and better engage the community.

- Computational platforms are evolving rapidly, and sharing infrastructure across science areas will greatly improve our ability to respond to, and take advantage of, these evolving platforms.
- There is increasing overlap in critical applications for climate, weather, chemistry, and geospace research. A unified modelling system will help bring together these communities by allowing scientists to "speak the same language" through a common code infrastructure.

The primary goal of SIMA is to enable frontier science in climate, weather, atmospheric chemistry, and geospace research in a unified modeling system. As illustrated in the schematic, SIMA would be the atmospheric component of an ESM composed of a series of interoperable pieces or components (i.e., dynamical cores and parameterizations for heat, moisture, trace gases and aerosol processes) with a shared and community infrastructure (i.e., code repositories, i/o formats, setup scripts, analysis tools, etc.) where possible.

Science applications in climate, weather, atmospheric chemistry, and geospace require atmospheric models with a broad range of capabilities. The community, spearheaded by NCAR, has worked to develop, maintain and support atmospheric models to meet the research needs for these applications. While the focus of SIMA is on the atmosphere, the modeling system we envision is part of an Earth System Model (ESM, see schematic). In particular, many of the science goals identified as drivers for the development of SIMA require the connection of SIMA to other components, such as an ocean model, as well as data assimilation systems. SIMA will provide a hierarchy of atmospheric configurations. SIMA will also be able to couple to a hierarchy of other component models (land, ocean, etc)., so complexity can range from prescribing a dataset as a boundary condition to a fully interactive dynamical component.



Schematic of different SIMA configuration options. Acronyms used here and elsewhere are listed at the end.

SIMA will provide the hierarchy of atmospheric model configurations needed to address the broad range of SIMA science questions. This includes SIMA configurations for prediction across spatial and temporal scales ranging from high impact, regional weather, which will include data assimilation capabilities, out to centennial-scale climate prediction. SIMA is a continuously evolving research modeling system and it is not being developed for operational applications. However, as a freely available community modeling system, community members and other entities are free to adapt it for use in operations as has often been done, for example, with the WRF model.

Data assimilation (DA) is an essential component of SIMA. The development and application of DA approaches is a major research area, and SIMA will leverage existing community DA systems, including the Data Assimilation Research Testbed (DART) centered at NCAR and the Joint Effort for Data assimilation Integration (JEDI) being developed by the Joint Center for Satellite Data Assimilation.

We envision an evolution with an initial evaluation phase to share and examine the suitability of different components for shared applications; thus, the system will evolve over time toward a single shared system (a set of varied components with common infrastructure). The infrastructure will be designed from a full set of SIMA requirements that enable the frontier applications. More implementation details of this ‘roadmap’ are below.

Initially, SIMA will combine existing models, dynamical cores, and physics packages into a common modeling system that will enable tackling new frontier science problems and advancing new modeling capabilities with efficient model development. SIMA will be configurable to produce an atmospheric model that can be combined with various other Earth System Model components and data assimilation interfaces through a coupling architecture. Researchers will be able to configure SIMA to produce configurations similar to current very successful and widely used models (e.g., WRF, CAM, WACCM, WACCM-X, and MPAS) with shared software. Such a modeling system will draw heavily on existing community science (methods, dynamical cores, parameterizations), but will develop a common infrastructure to enable sharing of currently disparate components and software tools. SIMA will create new opportunities without eliminating the modeling capabilities that the community has now.

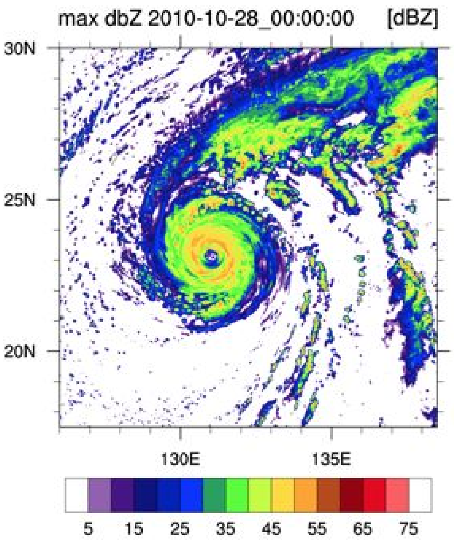
Similar unification efforts for other components of the environmental modeling system embodied in NCAR’s ESM (the Community Earth System Model, CESM) have already been expressed and work is underway (e.g. CTSM for land and MUSICA for chemistrfy). The unification of the atmosphere model has lagged behind, with weather and climate following separate paths within NCAR. SIMA is primarily an effort to address that separation.

Frontier Science

Several key frontier science applications have been identified. The workshop participants developed several examples of high impact and high potential applications. These are listed below for short term (weather) prediction of coupled phenomena, extreme events in climate, polar prediction, space weather, and biomass burning and air quality. The examples at the end of each section are desired configurations, though other configurations have been used to target the application. The examples do not require to combine all configuration options or complexity available in SIMA to make progress on the science questions, they are not the only possible configuration to address a specific problem or science question. For example, not all science problems require full chemistry or data assimilation.

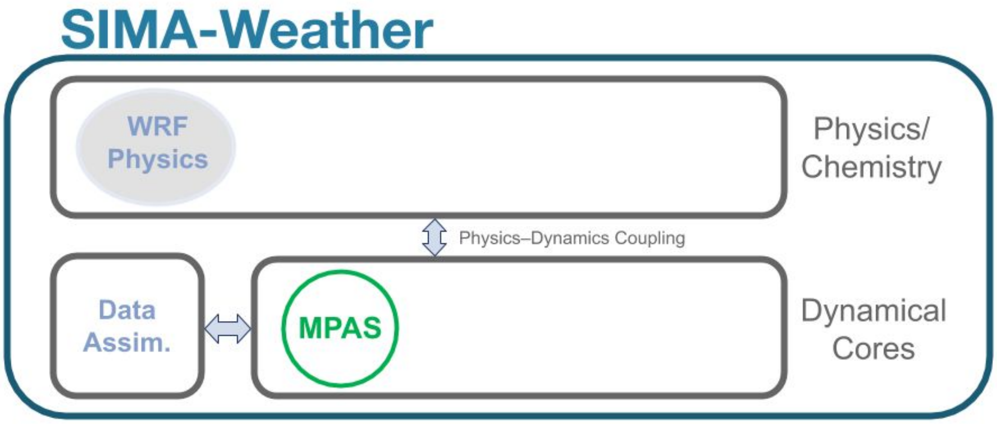
Tropical cyclone predictability

What is the predictability of tropical cyclone (TC) formation from short (1 day) to extended range (30 days)?



Simulated radar reflectivity of typhoon Chaba from a global MPAS simulation using a 3-km mesh.

To understand predictability of TCs, it is necessary to understand TC formation processes, and the mechanisms underlying the interaction between TCs and the larger scale circulation and ocean surface. Dynamics underlying these problems involve the atmosphere, ocean, land, and their interactions across a range of scales, such as atmospheric convection and its interaction with larger-scale atmospheric circulation, ocean–atmosphere interactions, and the influence of Saharan dust on tropical convection through radiative and microphysical interactions. A convection permitting atmospheric model (Δx < 5 km) complete with aerosol–cloud–atmospheric interactions coupled with an eddy-resolving ocean model (Δx < 1/12 degree), will produce detailed simulations of TCs and their earth-system interactions for even the strongest TCs. Such a model could have focused high resolution only over a tropical cyclone basin (e.g., the subtropical Atlantic ocean and Carribean sea). Combining SIMA with data assimilation systems will provide for even further understanding of physical processes in the tropics and identify paths toward improved physical parameterizations for tropical weather. These scientific results will also help address longer timescale questions related to the role of TCs, their character and their predictability, in future climates.

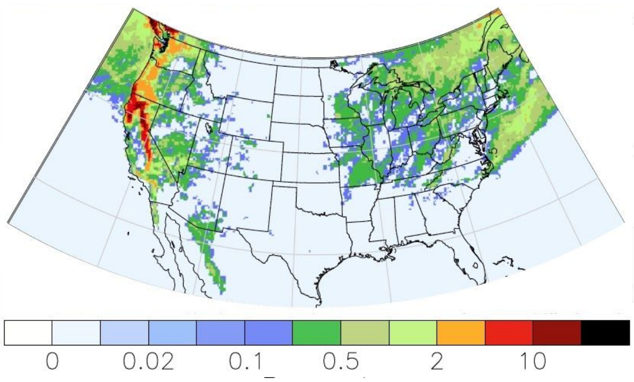


SIMA Schematic for Weather Applications with WRF physics, MPAS non-hydrostatic dynamical core and Data Assimilation. Such an atmosphere model would be coupled to an interactive ocean.

Extreme events in climate

How will extreme weather events change regionally under climate change?
How will regional and global hydrological cycles change under climate change?

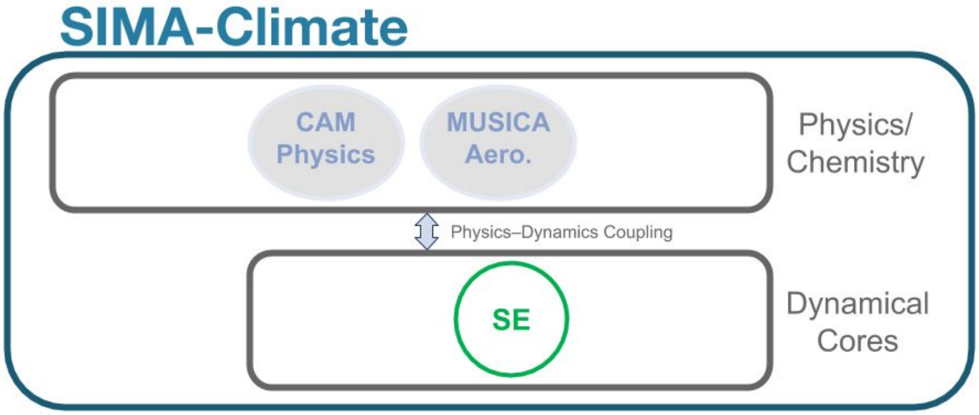
A critical challenge in climate and hydrological research is predicting the distribution of extreme transient weather events (thunderstorms, mesoscale convective systems, tropical cyclones) and their impact on the hydrologic cycle. Hydrological extremes in the form of the extreme presence (flood) or absence (drought) of water, are critical for prediction on many scales, particularly seasonal and longer timescales. Understanding risks of flood and drought, and how they may change from region to region are critical societal needs. Precipitation is particularly challenging to assess and predict, because variability and processes span many scales: from cloud microphysics (micrometers) to organized convection (1 to 100 kilometers) to synoptic systems (100s of kilometers).



Fractional Occurrence of Graupel as a percent in a 14km refined mesh global simulation showing extreme orographic precipitation in winter.

We are presently at a unique time where new methods and ideas from across the sub-disciplines of atmospheric and climate science can be brought to bear on the problem of representing precipitation. High-resolution simulations feature complex representations of processes for precipitation formation, relying on more explicit resolution of the cloud dynamics at weather scales. For example, the figure above shows the frequency of occurrence of graupel, an indicator of extreme and damaging precipitation, in a configuration of a global climate model (CESM 2) with modified cloud microphysics run with a mesh refined to a 14km resolution over the United States. This is an attempt to duplicate the features and complexity found in most mesoscale weather models, but at timescales more relevant for climate studies (this model was run for several years).

Weather models (e.g., WRF) are being used in similar fashion to capture high impact weather at convective permitting resolutions scales (< 5 km) over seasonal to annual scales. While able to capture much of the important weather phenomena, these models do not currently have the capability to couple to other earth system components in a global or regional configuration. But, traditional weather models also do not have features necessary for long timescales. Earth system models (ESMs) bring interactive land and ocean surfaces, conservative transport, and closed energy budgets that are important for representing longer timescales. Thus there is benefit in combining ongoing efforts. An ESM based on advanced atmospheric components that can provide simulations down to the 4km scale will enable an understanding of the frequency and intensity of weather extremes for future climate states.



SIMA schematic for Climate Configuration with the Spectral Element (Refined Mesh) dynamical core, CAM physics and aerosols. Such a configuration could also use modified weather model physics. For weather extremes, full chemistry is not necessary.

Coupled Prediction of the Arctic

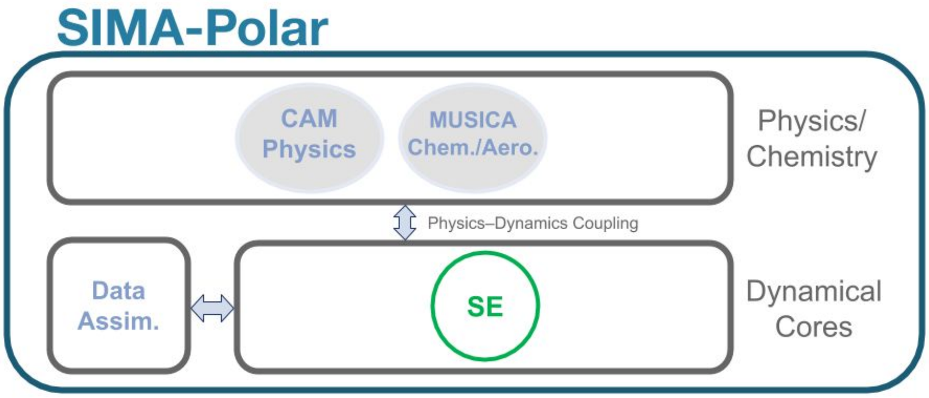
What processes in the Earth system control predictability in the Arctic?
What processes govern the mass balance of the Greenland Ice Sheet?

One particular area where weather and climate come together is in understanding processes that control predictability of polar regions, especially the Arctic. Predicting the Arctic is critical to the safety of indigenous communities, to expanding transportation in the Arctic, and to understanding future global change.

Streamlines of wind over the Greenland ice sheet from a 1/8˚ refined mesh CESM2-Greenland Ice sheet grid. Visualization from Matt Rehme (CISL) and Adam Herrington (CGD)

Many Arctic research problems epitomize coupled system science by involving the atmosphere and aerosols, land surface, biogeochemistry, cryosphere (including snow, ice sheets and sea ice) and ocean. Predictability on sub-seasonal to seasonal (S2S) and longer timescales exists due to the persistence of ice and ocean conditions and coupled interactions. One important example is the surface mass budget of the greenland ice sheet. Understanding the critical processes that contribute to it is important for global sea level.

Resolving the fine scales that strongly influence Arctic predictability motivates the use of refined mesh models that deploy high resolution (5-10km) where it is needed. A high resolution atmosphere can represent the detailed response to topography, land ice, and oceans temperature gradients. For many Arctic problems, a high resolution atmosphere must be coupled to oceans and sea ice components. Such a coupled system could include data assimilation for S2S prediction of quantities, like the mass balance of the Greenland Ice sheet.

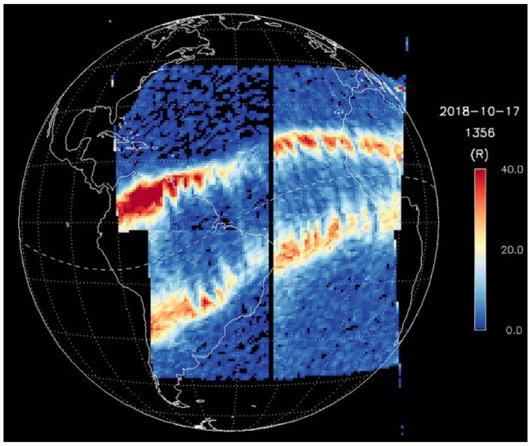


SIMA Polar schematic showing the atmosphere mode (in an ESM) used to simulate the Greenland ice sheet with the refined mesh Spectral Element Dynamical core, data assimilation, CAM physics and MUSICA Aerosols. The SIMA atmosphere would be coupled to ocean, sea ice and land ice models in an ESM (not shown).

Geospace and Atmosphere Interactions

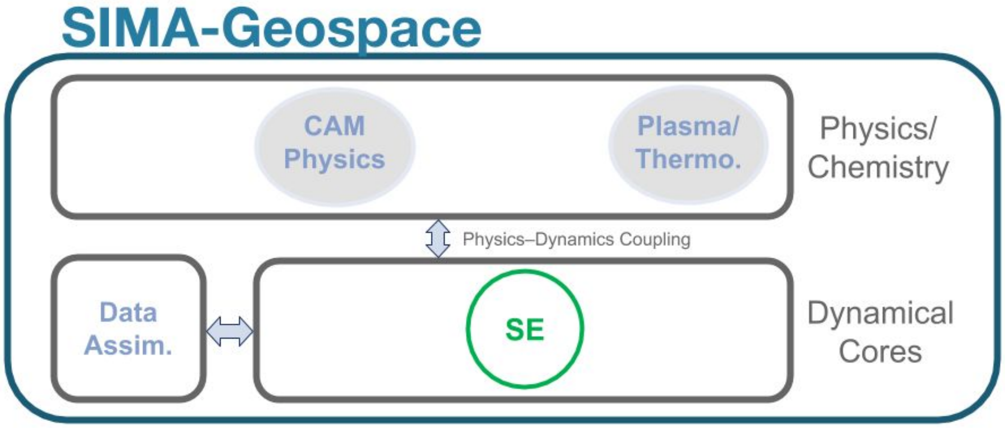
How do multiscale processes and interactions affect geospace-atmosphere coupling and space weather?

Space weather events that impact technological systems are especially manifested in the ionosphere and thermosphere. These include disturbances with scales from global to mesoscale such as absorption events from solar flares and energetic particles, ground-induced currents due to highly variable ionosphere-magnetosphere currents, thermospheric density anomalies that affect orbital dynamics, and small-scale plasma instabilities that cause scintillations in radio wave propagation.



Caption: Image of equatorial ionization anomaly (EIA) and plasma depletion *(bubbles) by the NASA Global-scale Observations of the Limb and Disk (GOLD) instrument. The plasma bubbles are the darker streaks across the bright EIA bands.*

The geospace effects on radio communications are well-known, and disruptions of navigation systems are increasingly important, especially for precision applications such as in aviation and for the geospace impact on power grid and continental pipelines. Understanding and forecasting space weather is critical for low earth orbit (LEO) orbiting objects.The ionosphere and thermosphere disturbances are generally known to be caused by both solar, geomagnetic and lower atmospheric forcings that occur at a variety of spatial and temporal scales. However, cross-scale interactions of the forcings are poorly understood, requiring a comprehensive modeling approach to integrate traditional atmospheric models with specialized geospace models for the ionosphere, plasmasphere and magnetosphere. This can be achieved by a SIMA configuration as shown in the SIMA Geospace schematic. Sophisticated data assimilation techniques will enable integration of diverse measurements into theoretical descriptions. High-resolution modeling capabilities are also necessary to capture small-scale and impactful space weather events, such as the onset and development of ionospheric equatorial plasma bubbles, as shown in the GOLD image. The SIMA geospace configuration will also enable advances in other frontier science questions discussed during the workshop, for example, the impact of climate change and extreme weather on the space environment and the effect of geospace-atmosphere interaction on surface weather and climate.



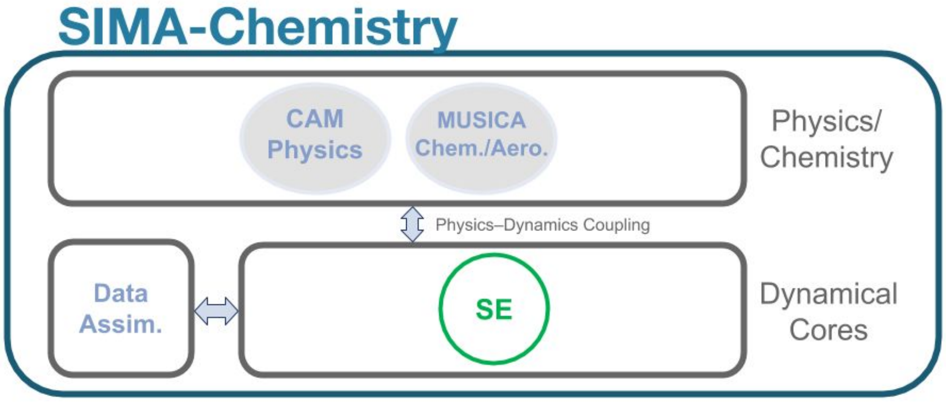
SIMA Schematic for Geospace Simulations including thermosphere physics and plasma physics (ionosphere, plasmasphere and magnetosphere) and the Spectral Element dynamical core.

Biomass Burning Effects on Air Quality, Weather, and Climate

How does biomass burning impact air quality and atmospheric chemistry from local to global scales?

Wildfire photograph taken during the WE-CAN field experiment by Frank Flocke

Biomass burning, which includes wildfires, prescribed burning, agriculture fires, and residential wood combustion, is the largest combustion-related source of organic compound emissions to the atmosphere. Yet, the inability to model well the emissions, transport, chemical transformation, and fate of these organic compounds has meant that there are large uncertainties surrounding their true impacts on, and feedbacks from, humans, weather, climate, visibility, and ecosystems. An integrated modeling framework is needed that will allow for better predictions of biomass burning emissions and impacts to enable extreme event risk assessment and to inform mitigation strategies. Air quality forecasts impacted by biomass burning will benefit from an advanced chemical data assimilation capability to constrain key constituents. The unique aspect of biomass burning is its strong interactions with land, vegetation, weather, and air quality as well as climate conditions. Thus, SIMA is envisioned to be configured to provide high resolution atmosphere grids in fire-prone regions of the world and coupled with a sophisticated land model. But SIMA could also provide both regional context of weather and climate, and impacts of the biomass burning on urban areas and continental scales. Such integrated modeling advances are likely to aid in the design of technological and policy interventions to mitigate the occurrence and impacts of biomass burning, ranging from, for instance, the development of early-warning systems for fire-impacted regions in the Western United States to programs that accelerate adoption of cleaner cooking and heating fuels in the low- and middle-income countries. The capabilities introduced for biomass burning will also help evaluate compliance with air quality standards in light of increasing background levels of ozone and particles, spatiotemporal distribution of pollutants in mountainous and coastal regions, and understanding the impacts of long-range transport of anthropogenic pollutants to polar regions.



SIMA Schematic for Chemistry configurations including the regionally refined Spectral Element dynamical core, data assimilation for near term prediction, CAM physics and MUSICA chemistry and aerosols. Such a configuration will also be coupled to a land model.

SIMA Community Engagement

The SIMA vision is of a unified atmospheric modeling system housed and maintained at NCAR but designed,developed and governed with the research community. The SIMA vision and implementation are the results of ongoing community engagement. SIMA intends to build upon existing community atmosphere models with extensive community education, documentation, analysis packages and community governance.

Providing tutorials, thorough documentation, and user's guides is key to enabling a large community of users. SIMA will build on experience that has shown how active and robust tutorials successfully and rapidly train users (mostly graduate students, but all career levels attend) to understand and run models. Tutorial instructors and documentation authors will be a combination of experts from NCAR and the community. SIMA will provide a comprehensive hierarchy of idealized or simplified configurations that can be used for research and teaching. Virtual and in-person exchanges between NCAR and community members's institutions to work with SIMA will be encouraged and facilitated.

SIMA will build on existing evaluation and metrics packages currently used with the modeling components that initially comprise SIMA for evaluation of weather, climate, chemistry and geospace. These packages will be brought into a common model infrastructure and workflow to accelerate research progress on Frontier Science by combining evaluation across modeling components that serve separate communities with traditionally distinct diagnostics.

An equally important part of community engagement is the design and implementation of community collaboration and governance structures. NCAR and the community have shared experiences developing and maintaining existing successful community modeling systems, and SIMA will build on that. Community governance means community engagement in setting priorities. Community governance will play a critical role in SIMA model development and help ensure that SIMA development goals are aligned with evolving scientific foci and capabilities of the community.

From Here to There: After the Vision

SIMA is an opportunity to combine and reimagine NCAR's tremendous science capabilities in many areas of atmospheric modeling, from weather to climate to chemistry to geospace and prediction in new ways to advance knowledge and better serve society. Given the tremendous human capital in the community and at NCAR, the capability to do this is within our grasp.

The SIMA Frontier Science questions encompass ESM applications requiring most of the atmospheric model configurations desired by the community. The development and testing of SIMA within the conduct of that science is at the heart of the SIMA program and guides SIMA development and prioritization. SIMA will adapt existing model components, codes and configurations into a coherent system. SIMA will add new functionality and new methods as appropriate. A separate SIMA implementation plan outlines steps for NCAR and community partners to make progress on achieving this vision as we evolve SIMA together.

Acronyms

SIMA System for Integrated Modeling of the Atmosphere
WRF Weather Research and Forecast model
MPAS Model for Prediction Across Scales
CAM Community Atmosphere Model
CESM Community Earth System Model
CTSM Community Terrestrial System Model
WACCM Whole Atmosphere Community Climate Model
WACCM-X includes geospace modeling capability
FV Finite Volume dynamical core
SE Spectral Element dynamical core
MUSICA MUlti-Scale Infrastructure for Chemistry and Aerosols
Plasma/Thermo Physics & chemistry of the plasmasphere,ionosphere and thermosphere