Future Directions for the Earth System Modeling Framework

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Summary *We outline here a vision for the evolution of the Earth System Modeling Framework (ESMF) into a comprehensive Earth System Modeling and Assimilation Environment (ESME). ESMF is making rapid and sustained progress towards its goal of changing the culture and software infrastructure of Earth system modeling in the U.S. These advances have the potential to make Earth system models a mature tool in our scientific, operational, and policy repertoires over the coming decades. We describe how Earth system models might be configured, run, and analyzed when a full panoply of possibilities is placed in the hands of the individual researcher; and the fundamental and essential role that the ESMF might play in this evolution if it continues to be developed over the long term. In this vision, the ESME will serve as a uniform launching pad for all ESMF-compliant applications; be deployed for both research and at operational centers; allow archival, retrieval and comparison of model configurations and output from existing model runs; allow the same model configuration to be run by multiple models for ensemble and intercomparison studies; permit scientific queries across linked published studies, datasets and models; and permit models to be optimally configured when switching platforms. By linking universities, operational centers and research centers under a common computational framework, the ESMF, and to an even greater extent the ESME, will enable the scientific advances of the researcher to be transitioned quickly to key forecasting and prediction applications.*

1. Introduction

The NASA-funded Earth System Modeling Framework (ESMF)[1] effort has brought together the leading climate, weather, and data assimilation groups in the U.S. in the interest of creating a common software infrastructure. The initial goals of the ESMF

[1] http://www.esmf.ucar.edu

project are in the area of software improvement: greater interoperability of software among major modeling centers, efficiency of development through shared software systems, standards and utilities, and increased application robustness, portability, and performance.

The results of the ESMF promise to be much further reaching than software improvement. The groups engaged in this enterprise, including the NSF National Center for Atmospheric Research, the NOAA Geophysical Fluid Dynamics Laboratory and National Centers for Environmental Prediction, the DOE Argonne National Laboratory and Los Alamos National Laboratory, the NASA Global Modeling and Assimilation Office, the University of Michigan, and the Massachusetts Institute of Technology, are at the forefront of Earth system modeling in the U.S. In parallel to the development of ESMF, NASA also supports the development of the complementary Space Weather Modeling Framework (SWMF)[1] that extends synergistic common software infrastrucure to the Sun-Earth environment. The ESMF project has fostered unprecedented communication and collaboration among these diverse modeling groups. The new applications being generated by the project, featuring never-before coupled configurations, hold the promise of new science. A successful ESMF program will result not only in improved, interoperable modeling software, but a modeling community with exciting new opportunities for collaborative research, and the social and technical infrastructure poised to take advantage of them.

We begin by reviewing the history of the ESMF in Section 2. Section 3 contains a brief description of the framework, and a summary of the current project status. In Section 4 we outline the next step in ESMF development, its extension into an integrated Earth System Modeling and Assimilation Environment (ESME). In Section 5 we discuss some of the practical, near-term aspects of realizing this vision. Several of the key science initiatives enabled by the framework are described in Section 6. In Section 7 we place the ESMF/ESME in the context of national policy, and present a case for continued multi-agency funding. Conclusions are in Section 8.

2. Background

The ESMF collaboration has its roots in the Common Modeling Infrastructure Working Group (CMIWG). The purpose of this unfunded, grass-roots working group is to explore ways of enhancing collaborative Earth system model development. The CMIWG attracts broad participation from major weather and climate modeling groups at research and operational centers, and topics have covered both data and modeling infrastructure. In a series of meetings held from 1998 to 2000, CMIWG members established general requirements and a preliminary design for a common computational framework.

[1] http://www.csem.engin.umich.edu/SWMF

In September 2000, the NASA Earth Science Technology Office (ESTO) released a Cooperative Agreement Notice entitled *Increasing Interoperability and Performance of Grand Challenge Applications in the Earth, Space, Life and Microgravity Sciences* that called for the creation of the ESMF. A "critical mass" of CMIWG participants agreed to develop a coordinated response, based on their strawman framework design, and submitted three linked proposals. The first focused on development of the core ESMF software, the second on deployment of ESMF modeling applications, and the third on deployment of ESMF data assimilation applications. All three proposals were funded, at a collective level of $9.8M. [1] The complementary SWMF project was also funded, envisioned as part of the broader ESMF. [2] As the ESMF project has gained momentum, the forum for infrastructure development within the community has shifted from the CMIWG to the ESMF; from the articulation of a plan to the building and deployment of a product.

3. ESMF Project Description and Status

The ESMF consists of a **superstructure** for coupling components of Earth system applications, such as atmosphere and ocean models; and an **infrastructure** of robust, high-performance utilities and data structures that ensures consistent component behavior. User code is "sandwiched" in between the two layers, as shown in Figure 1. A comprehensive description of the ESMF architecture is provided in [3].

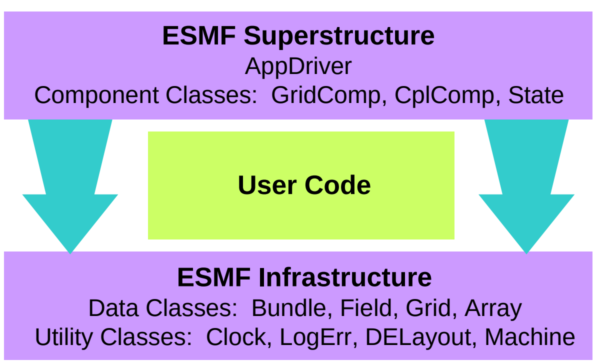


Figure 1. *The ESMF sandwich architecture. ESMF software consists of*

i. a superstructure for coupling model components and assembling them into applications

ii. an infrastucture of data structures and utilities for building model components

At the end of its initial funding cycle, the ESMF collaborators will deliver a viable version of the core framework together with 15 ESMF-compliant applications, including the Community Climate System Model (CCSM) [4], the NCEP Global Forecast System [5], models from the GFDL Flexible Modeling System (FMS) suite [6], the Weather Research and Forecast (WRF) Model [7], the Estimating the Climate and Circulation of the Ocean (ECCO) systems [8], and the new GMAO modeling suite. The on-line *ESMF Component Database* [9] catalogues ESMF testbed applications. The SWMF will deliver a first-generation framework with 9 applications, including a Solar Storm Generator, Inner Heliospheric Model, Global Magnetospheric Model, Upper Atmosphere Model, and Radiation Belt Model.

The ESMF project is presently about halfway through its initial three-year funding cycle. Proof-of-concept was demonstrated in a prototype release on May 15, 2003; since then the project has been issuing monthly internal releases. The next major public release is anticipated to be on schedule, in May, 2004. A new *ESMF Partners* program has brought in a number of additional application groups, including the NASA Goddard Institute for Space Studies (GISS), UCLA, the NASA Goddard Land Information Systems project, the DoD Naval Research Laboratory, and the Center for Ocean-Land-Atmosphere studies. The project is proving to be a success, both in terms of the progress made in software engineering, and in the acceptance and participation of the community in the ideas and vision that it represents. An *ESMF Industry Partners Forum* was established at Supercomputing 2003. The industry forum provides, for the first time, a unified channel for the Earth system modeling community to present their fundamental system needs to software and hardware providers.

4. Towards an Earth System Modeling and Assimilation Environment

The ESMF is an essential technological foundation for Earth and space modeling: it facilitates performance portability, increases software reuse and efficiency of development, and helps to architect very complex models so that new features can be added easily. By enabling the interoperability of model components, it fosters collaboration and technology transfer from research to operations. However, it does not represent a full solution to the technical difficulties encountered in Earth and space system modeling. These difficulties include:

- the gulf that separates the formulation of a scientific question about the Earth system, and the configuration of an Earth system model to answer that question;
- the inability to query the vast volumes of observational and model output data that is available at various sites in a scientifically meaningful way;
- the daunting level of expertise that must be marshalled for running models on a variety of platforms, and for scientific analysis of distributed datasets.

We believe that many of these barriers can be overcome over a cycle of scientific software renewal, and that the seeds of a solution are present in the ESMF. As with much scientific technology, original and innovative techniques that enlarge a researcher's horizons begin by being technically abstruse, then become routine and recede into the background of things taken for granted. This process is now underway in our field as well.

ESME benefits …

Climate scientists: setup (assemble components, configure input parameters); comparisons of models, data, results; branch runs from existing runs; link published results, datasets and models.

Impacts modelers: impacts models are run offline (and increasingly in coupled mode) from existing climate runs: ESME will permit impacts modelers to query a database for suitable models, and configure and launch their own runs from it.

National and international assessments: the IPCC and various MIPs (model intercomparison projects) require a single setup to be run across multiple models. The ESME will permit easy setup of such experiments, as well as provide access to results from these studies.

Policymakers, industry, and educators: high-level access to models and data.

Operations: higher rates of technology transfer from research to operations, automatic best practice while switching platforms.

By design, in its initial phase the ESMF concentrated on the modeling component code infrastructure and the coupling superstructure, with deployment of major U.S. climate and weather models and data assimilation systems. Having developed the necessary software tools for coupling Earth system components in this initial phase, it is natural for the ESMF to evolve into a more complete problem-solving environment. The key insight we have gleaned from the design and prototype development of ESMF-based models is that the files that are used to configure, build and launch a model contain the same physical content that must be written to the output dataset for a comprehensive description of how the model data was created. This information would be stored in a relational database of model configurations and datasets that would become the central element in the ESME. The curator database would permit a uniform interface to models and datasets: allow comparisons, queries, links across models, data and published results, and finally make possible the vision of ESMs being a regularly and routinely deployed tool in the science, operational and policy repertoires.

With the ESMF in place, we may begin to take the first steps toward the broader goals of the ESME. The following are key elements of the ESME which could be produced over the next development cycle:

- **Integration of data and models**. As data is an essential element of Earth system modeling, a concerted effort is required for the development of comprehensive data components, and integration of the ESMF/ESME with other national and international efforts such as the Earth System Grid (ESG) [10] and the European analogue to ESMF, the Programme for Integrated Earth System Modeling (PRISM) [11]. Essential to this vision is the development of standard set of data and model descriptors (a "semantic web"), and a system for instrumenting models so that they can produce such descriptors automatically. A key benefit of this integration would be seamless access to the wealth of present and future satellite observations by models and data assimilation systems.

- **Development of a community database** containing 1) ESMF-based modeling components, data assimilation components, and the couplers that can be used to combine them into applications and 2) modeling experiments containing configuration parameters, notes and references, and other information associated with particular model runs. We would expect to develop this database in collaboration with PCMDI [12] and other community initiatives. Accompanying the database would be a query facility, tools for determining technical (not scientific) compatibility of components, and tools for the automatic generation of couplers.
- **A launch/monitoring facility** for managing the execution of complex ensembles of Earth system models and data assimilation systems. ESMF will leverage Globus/GRID services [13] as they mature, so that researchers can exploit a pool of common computational resources.
- **A web portal** that integrates the above services in a manner sensitive to scientific workflow. Integration with client and server side data analysis and visualization.

Figure 2 illustrates the structure of the ESME and the end-to-end scientific workflow that it will facilitate.

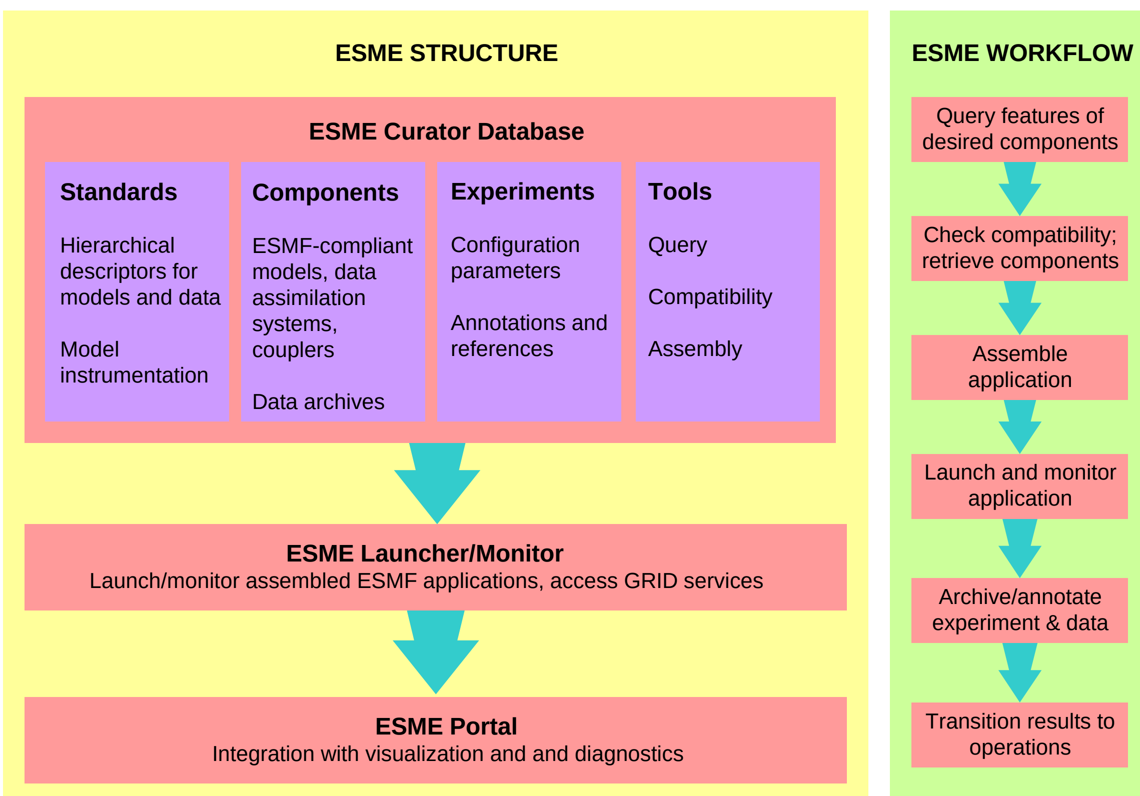


Figure 2. *Elements of the ESME, including the curator database, launcher/monitor, and web portal; and*

the integrated, end-to-end workflow that the ESME will enable.

This section has provided a preliminary sketch of the scope of the ESME. ESMF collaborators, in conjunction with CMIWG members whose interests lie in data services and diagnostics, intend to refine this vision through a series of meetings similar to those that led to the development of the framework. Key new partners anticipated include PCMDI, ESG, and PRISM.

5. Realizing the Potential of the ESMF

The initial period of funding of the ESMF will result in significant advances, and a robust software product. However, software requires maintenance and support to remain viable. To simply secure the gains in technical and social infrastructure achieved thus far, and to complete the original requirements laid out for the ESMF, it is essential that the ESMF project be supported beyond its current 3-year term. We anticipate that it will take several years for ESMF to be well established in production applications throughout the community, and for continued work on the software to consist primarily of maintenance.

Developing a sustainable strategy for ESMF development beyond its initial funding cycle requires balancing the requirements for robust, efficient software and prompt user support whilst leveraging contributions from the user community. The ESMF is being developed as open-source software by a core implementation team at NCAR, supplemented with contributions from developers at other sites. In order to encourage broad engagement, and provide a clear and simple method for providing input, the ESMF team maintains a public software repository for user contributions. It is expected that the user community will provide, for example, new grid representations and regridding code, support for additional I/O options, diagnostics toolkits, visualization components, ports to new platforms, ESMF-compliant components, and other software. ESMF users are already actively developing contributions in some of these areas and it is anticipated that many more contributions will become available as the core framework matures.

However, while user contributions will provide some aspects of maintenance, they do not provide the guaranteed maintenance and support that is essential for a product used in critical applications. The proximity and close coordination of the implementation team and its technical leadership are essential for a coherent, exhaustively tested, consistently documented product. *The viability of ESMF depends upon the continued existence of a dedicated team that can coordinate development and provide user support.*

Resources must also be appropriated to continue to support ESMF education and integration into applications. As the ESMF software matures, an increasing number of applications will explore and then adopt ESMF as a software tool. In support of these efforts, the ESMF customer support team must have application experts available to assist with familiarization and integration. For a handful of key application areas, dedicated staff working with the application groups for an extended period will be required to facilitate integration of ESMF into the production versions of applications. A targeted outreach program can provide support to early adopters and encourage new users.

In the Appendix we discuss in more detail the resources required to implement and deploy core ESMF capabilities.

6. Enabled Science Initiatives

ESMF will unleash the formidable talents of the US modeling community, reducing duplication of effort so that the sum of the parts is greater than the whole, and allowing new science to be pursued with vigor. The following are key science initiatives enabled by ESMF.

1. **Seamless Prediction Across Timescales.** ESMF is already facilitating the organization of components within institutions as well as collaboration among institutions. It is, for example, being used at Goddard to develop a unified modeling system for climate, weather prediction, and data assimilation applications that depends on contributions from several institutions. The framework is also central to the NASA/NOAA Joint Center for Satellite Data Assimilation, in particular their collaboration on the development of a single atmospheric data assimilation system to satisfy the needs of both agencies. When completed, this development will result in much better utilization of both satellite and conventional data and an unprecedented level of technology transfer between these institutions. ESMF will also facilitate the interaction of data assimilation systems with atmospheric and oceanic models. This capability is already being used in the NASA/NOAA collaboration, but it has other important applications. The groups at NCAR and Goddard are developing these assimilation systems as a means of analyzing physical parameterizations by studying analysis errors, and validating climate models by performing short-range and seasonal predictions.

2. **Advanced Earth System Modeling.** One of the areas of primary interest to the Earth modeling community, at centers such as GFDL, NCAR, Goddard, and MIT, is the integration of atmospheric chemistry and ocean biogeochemistry into a coupled model for full carbon cycle studies. By treating the chemistry codes as ESMF components, it will be possible to introduce them into coupled climate models and assimilation systems in a straightforward manner. ESMF will also become the enabling software technology of the ECCO project, a collaboration

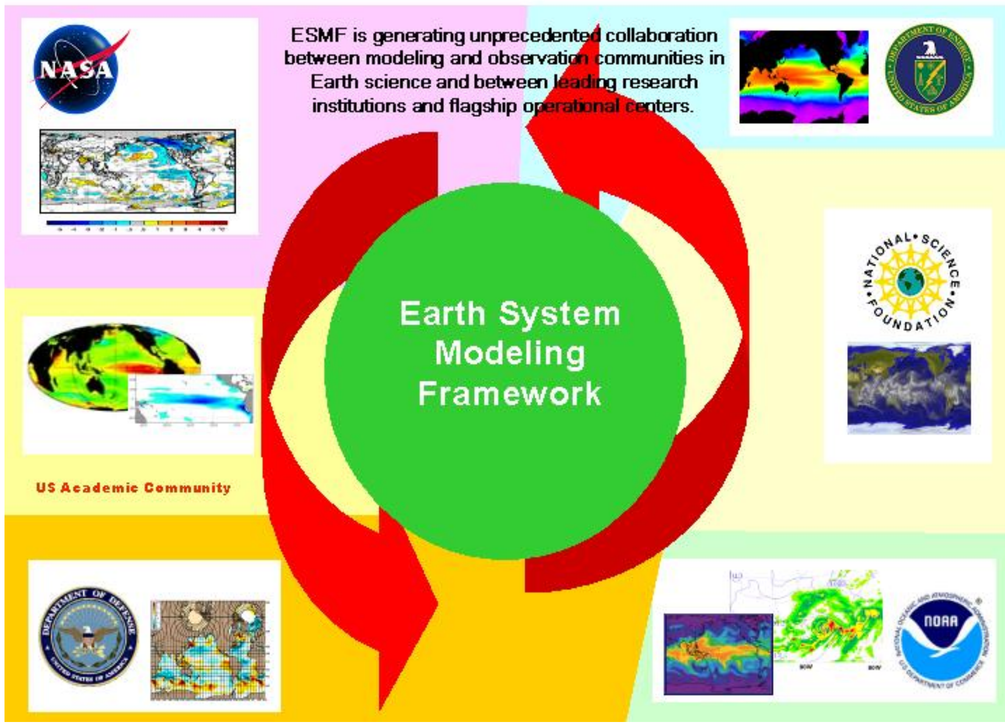
between MIT, JPL and Scripps. Future ECCO plans involve coupled (atmosphere and ocean) estimates of biogeochemical properties and air-sea fluxes of CO2 and O2, addressing questions such as the partitioning of carbon between the atmosphere, ocean and the terrestrial biosphere.

3. **Integrated Earth/Space System Modeling.** By using ESMF and SWMF, modelers at the Universty of Michigan and elsewhere will be able to link Earth and space models in order to explore solar storms and their technological and human effects. This area of research is of growing scientific and societal interest.

4. **Downscaling with Embedded Regional Models.** ESMF will facilitate the incorporation of regional atmospheric and ocean models into global climate models for the purpose of regional prediction and downscaling. Such an effort involving the Community Climate System Model (CCSM) and the Weather Research and Forecast Model (WRF) has been recently proposed. ESMF will be the technical substrate that enables these complex components to be combined in to a single application.

5. **Community Ocean Modeling.** In the oceanic community new efforts such as the Hybrid Ocean Modeling Environment (HOME) will be based upon ESMF. This project promises to bring together key U.S. developers (from GFDL, the University of Miami, Los Alamos, Stennis and Oregon State University) of isopycnal ocean models. The project is being conceived with an assumption that ESMF will provide a unifying software platform for collaborative development of a next generation isopycnal model.

6. **High-Resolution Earth Simulation.** ESMF is designed to enable climate modelers to exploit the biggest and fastest compute farms. Moreover, because a critical mass of the community is invested in ESMF it will facilitate the efficient use of such facilities by all. Global, cloud-resolving models are our goal, coupled with ocean models that resolve the mesoscale eddy field. Only when these key processes are resolved, rather than parameterized in our models, can our estimates of the present state of the climate and its future possible evolution be significantly improved.



7. ESMF in National Policy

ESMF must be viewed as the first step in the development of a long-term national program in order to reach its potential. This view is aligned with current U.S. policy and the findings of experts in the climate and weather domains. A number of reports have identified common modeling infrastructure as a key component of the U.S. climate change strategy [14,15]. The recent *Strategic Plan for the U.S. Climate Change Program* [16] recognizes the ESMF as the preeminent national Earth system modeling infrastructure effort and a means of facilitating collaboration among the nation's leading climate centers. Similarly, the NASA Earth Science Enterprise (ESE) Technology Strategy [17] cites the importance of the development of a common modeling framework that will allow diverse institutions to work on complex Earth system modeling endeavors.

We believe the time is ripe for a multi-agency commitment to fulfilling this vision. We outline here how ESMF/ESME coincides with the strengths and needs of our various partners:

National Aeronautics and Space Administration: NASA's data archives represent an extraordinarily valuable national resource. By allowing data assimilation systems to easily integrate with modeling applications, ESMF bring both NASA's expertise in data assimilation techniques and its vast data stores to bear on the improvement of models across a range of time scales. NASA has provided the vision and leadership that have guided the ESMF effort and have served to coordinate the national modeling community.

National Science Foundation: The NSF Cyberinfrastructure (CI) effort recognizes the critical impact of robust, innovative computational infrastructure on the geosciences. ESMF converges with the goals of the CI effort by deploying technologies that bridge the gap between large centers and individual university researchers. ESMF extends and leverages the CI effort by recognizing that research and operations are inextricably linked; that scientists in both camps require similar infrastructure and must have the capacity to transfer technologies.

National Oceanic and Atmospheric Administration: NOAA/GFDL is one of the cores of the national effort on climate change assessments, which require participation in intercomparison projects (IPCC,CMIP) as well as data analysis from multi-model ensembles. All of these benefit from technologies to be built in ESME. Both in short- and medium-range forecasting, as well as in the emerging fields of operational seasonal forecasting and operational climate assessments, NOAA centers will have access to seamless transfer of models between platforms, and enhanced rates of technology transfer from research to operations. NOAA/NCEP and the DoD run operational forecast models, and would benefit from the portability features and enhanced technology transfer from research to operations.

Department of Defense: The DoD has proposed the Battlespace Environments CyberInfrastructure (BECI) Institute, a distributed center that will integrate the ESMF into a variety of DoD applications from the Air Force, Navy, and Army. ESMF will provide the DoD with stable infrastructure for running applications within and across services. A key application for the BECI Institute is WRF, which is also an ESMF testbed. WRF will be used in integrated weather forecasts for the military. The DoD and NOAA are both operating space weather forecasting centers that will benefit from the extension of the ESMF so that it is compatible with the SWMF.

Department of Energy: The DoE has a long-standing interest in climate change, particularly at regional scales. The ESMF provides a mechanism for organizing and extending climate models, a task that has become increasingly onerous as models become more complex. Working together with the DoE Common Component Architecture (CCA) [18] effort, the ESMF is redefining the way climate models are structured, and enabling these models to harness a large family of new components developed by a broader community of computer scientists, mathematicians, and experts in related fields. On another front, the DoE ESG is being developed to fulfil the vision of seamless access to distributed model output data resources. By coupling these to standard component data structures, we may approach the goal of converging models and data. The DoE PCMDI effort addresses the scientific aspects of interoperability - the intercomparison and scientific validation of applications - and as such would be an appropriate and valuable partner to the ESME. Advanced gridding technologies in development at LBNL could also be brought in to ESME for easier adoption across the Earth system community.

8. Conclusions

The ESMF is a community effort to unite climate, weather and data assimilation groups under a common framework, and by doing so, fundamentally change the culture of Earth system modeling. The related SWMF extends its reach to the space community. To date the ESMF effort has shown rapid progress, and has begun to articulate a vision for the evolution of the framework into a comprehensive problem-solving environment, the ESME. Given the potential value of the ESMF/ESME to national interests, and the requirement for steady, ongoing support in order to bring this project to fruition, our collaborators propose a long-term, coordinated program of multi-agency stewardship.

References

1. National Aeronautics and Space Administration Cooperative Agreements, number NCC5-623 (Part I), NCC5-625 (Part II), GSFC-CT-3 (Part III).
2. National Aeronautics and Space Administration Cooperative Agreement, NCC5-614.
3. Hill, C., DeLuca, C., Balaji, V., Suarez, M., DaSilva, A. and the ESMF Joint Specification Team. The Architecture of the Earth System Modeling Framework. To appear in IEEE Computing in Science and Engineering, *Grand Challenges in Earth System Modeling*.
4. Boville, B.A. and P.R. Gent, The NCAR Climate System Model, Version One, *J. Climate*, vol. 11, 1998, pp. 1115–1130.
5. Kanamitsu, M. Description of the NMC global data assimilation and forecast system, *Wea. And Forecasting*, vol. 4, 1989, pp. 335-342.
6. GFDL Flexible Modeling System, http://www.gfdl.noaa.gov/~fms.
7. Michalakes, J.G. et al., Development of a Next Generation Regional Weather Researcgh and Forecast Model, *Proc. 9th ECMWF Workshop Use of High-Performance Computing in Meteorology*, World Scientific Press, 2001.
8. Estimating the Climate and Circulation of the Ocean, http://www.ecco-group.org.
9. Earth System Modeling Framework Component Database, http://www.esmf.ucar.edu, Applications.
10. Earth System Grid, http://www.earthsystemgrid.org.
11. PRISM, http://prism.enes.org.
12. Program for Climate Model Diagnosis and Intercomparison, http://www-pcmdi.llnl.gov.
13. Globus, http://www.globus.org.
14. Commission on Geosciences, Environment and Resources. Capacity of U.S. Climate Modeling to Support Climate Change Assessment Activities. Technical report, National Research Council, 1999.
15. Rood, R.B., J.L. Anderson, D.C. Baker, M.L. Blackmon, T.F. Hogan and P.K. Esborg. High-End Climate Science: Development of Modeling and Related Computing Capabilities. Technical report presented at OSTP, 2000.
16. Strategic Plan for the U.S. Climate Change Science Program: A Report by the Climate Change Science Program and the Subcommittee on Global Change Research.
17. Earth Science Enterprise Technology Strategy, http://www.earth.nasa.gov/Introduction/what.html.
18. Common Component Architecture, http://www.cca-forum.org.

Appendix: Maintenance and implementation of core ESMF capabilities

1. Maintaining the core activity

At this point in time, the ESMF project is about halfway through its initial three-year funding cycle. Its viability was demonstrated in a prototype release on May 15, 2003. The next major release is anticipated to be on schedule, in May, 2004. A new *ESMF Partners* program has brought in a number of new groups, including the NASA Goddard Institute for Space Studies, UCLA, the NASA Goddard Land Information Systems project, and the Center for Ocean-Land –Atmosphere studies. Overall, the project has shown growth that is rapid and sustained.

Continued support in the following areas is arenecessary to protect the initial investment in the ESMF software.

1.1 Routine Support, Maintenance, and Outreach

Two critical criteria for widespread software adoption are adequate user support and the assurance of software maintenance. Applications must believe ESMF is going to be viable for years for it to be seriously considered for production applications. Aspects of routine support and maintenance include user assistance with building and running ESMF, bug fixes, minor feature additions, and porting and optimization.

The last two items, porting and optimization, can represent considerable work. The high-performance computing environment changes rapidly, and the ESMF software must be modified and optimized for use with new computers. For some changes in the computational environment, such as shifts between vector and microprocessor-based platforms, new optimization strategies can result in major modifications to source code.

Basic outreach in the form of regularly scheduled tutorials and a yearly ESMF community meeting is also necessary. Beyond the three-year scope of the project, we estimate that two full-time support people will be adequate to address these needs. This support would *not* include working intensively with new users to modify their code for use with the framework; this could be covered in a targeted outreach activity (see Section 2.1 below).

1.2 Fulfillment of Initial User Requirements

ESMF development began with an exhaustive requirements collection process, and these requirements are being used to guide design and implementation of the framework. At the end of the initial three years of the ESMF project, it is likely that an additional two full-time software engineers will be required over the course of two years to complete the requirements that were first laid out. The areas that are not likely to be covered during the first phase include data structures for advanced data assimilation, support for high-performance I/O in a variety of formats, fault tolerance, and full support for nested grids. Functional extensions to the framework beyond the scope of the initial requirements are discussed in Section 2.2.

1.3 Establishment of ESMF in Key Applications

The later milestones for the ESMF project require that application groups involved in the collaboration deliver ESMF-compliant versions of their codes. In some cases, particularly the larger application efforts that are key for widespread framework adoption, the ESMF-compliant version that is delivered is expected to be on a development or experimental branch. In order to fully establish ESMF in the production versions of such codes, it will be essential to continue to offer modest programming support directly to the application groups. It can otherwise be very difficult to divert resources away from science development to investment in software infrastructure, despite the anticipated benefits. For these larger application efforts, a single full time support engineer in the year following the final ESMF delivery will significantly increase the likelihood of permanent ESMF adoption.

1.4 Sustaining Technical Oversight

The current ESMF architecture has been developed by a distributed technical leadership team working at NCAR, NASA GSFC, GFDL and MIT. This leadership team has been responsible for producing an architecture that is being widely accepted within the community. The technical leadership plays a critical role in translating the architectural vision into a realizable product and in refining architectural details as the project evolves. In order for ESMF to transition to a stable community standard this team should be kept in place for at least a further three years.

2. Growth and Development of ESMF

The following are efforts that would enrich the ESMF community and build on the framework's capabilities. Some of the following enhance scientific productivity in general; others target specific science goals.

2.1 Targeted Outreach

Outreach to new users and new communities may be effectively accomplished via the retention of one or more staff on the ESMF team who would provide more advanced user support and assist select modeling groups for longer periods. This support staff would mainly work with university groups and not the larger efforts that might have their own dedicated ESMF support engineer. The number of staff needed would depend upon how many groups adopt ESMF. The number might change over time.

2.2 Functional Extension

Grid support for adaptive and other advanced grids and more robust and accurate regridding methods are natural extensions to ESMF. Other functional extensions may be driven by the expansion of ESMF to accommodate related domains, as described in Section 2.3.

2.3 Domain Extension

The software infrastructure being created by the ESMF project has the potential to be of use in domains related to climate and weather, including solid Earth modeling, space weather, policy models, and ecosystem modeling. The challenges here are both technical - extending the ESMF functionality while retaining ease of use and performance; and social – extending into communities that are unfamiliar to the project team and management. The resources required here would depend upon the nature of the desired extension.