Emergence of the Earth System Modeling Framework

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Summary *The Earth System Modeling Framework (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 mature tools in our scientific, operational, and policy repertoires over the coming decades. By linking universities, operational centers, and research centers under a common computational framework, the ESMF 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 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 (NCAR), the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) and National Centers for Environmental Prediction (NCEP), the DOE Argonne National Laboratory (ANL) and Los Alamos National Laboratory (LANL), the NASA Global Modeling and Assimilation Office (GMAO), 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 a Space Weather Modeling Framework (SWMF)[2] 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

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

advantage of them.

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 mature common modeling infrastructure as a key component of the U.S. climate change strategy and other Earth modeling endeavors of national importance [1,2,3,4].

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.

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. [5] The SWMF project was also funded, envisioned as part of a broader ESMF. [6] 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 [7].

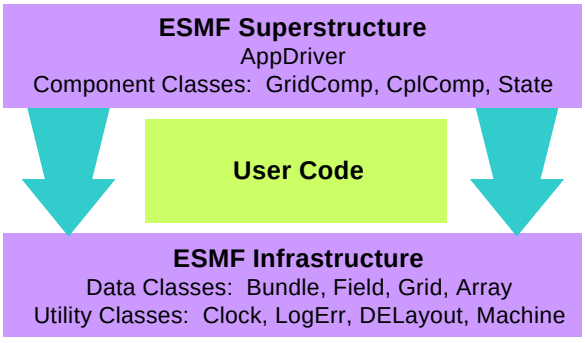

Figure 1. *The ESMF sandwich architecture. ESMF software consists of*

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) [8], the NCEP Global Forecast System [9], models from the GFDL Flexible Modeling System (FMS) suite [10], the Weather Research and Forecast (WRF) Model [11], the Estimating the Climate and Circulation of the Ocean (ECCO) systems [12], and the new GMAO modeling suite [13]. The on-line *ESMF Component Database* [14] catalogues ESMF testbed applications.

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. During March, 2004 the project completed the first three of eight "interoperability experiments" in which demonstration applications were created by combining never-before-coupled components from different institutions: the NCAR Community Atmospheric Model (CAM) [15] coupled to the NCEP Spectral Statistical Interpolation (SSI) system [16]; the CAM coupled to the MITgcm ocean model [17]; and the MITgcm ocean model coupled to the GFDL B-grid atmosphere running under FMS [see 10]. Future experiments will involve, among other models, WRF, the LANL CICE sea ice model [18], and the NASA Goddard GMAO ocean model [see 13].

A new *ESMF Partners* program has brought in a number of additional application groups, including the NASA Goddard Institute for Space Studies, 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 the SuperComputing 2003 conference. 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

By design, in its initial phase the ESMF project has concentrated on developing modeling infrastructure and coupling superstructure software, and deploying this software in major U.S. climate and weather models and data assimilation systems. Once this initial phase is completed, it is natural for the ESMF to evolve into a more comprehensive 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, stored in a relational database of model configurations and datasets, would become the central element of a next-phase Earth System Modeling and Assimilation Environment (ESME). The ESME 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 Earth system models being regularly and routinely deployed tools in 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 a future ESME:

- **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) [19] and the European analogue to ESMF, the Programme for Integrated Earth System Modeling (PRISM) [20]. Essential to this vision is the development of a 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 [21] 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 [22] 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, including client and server side data analysis and visualization.

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. 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 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 into 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 the goal, coupled with ocean models that resolve the mesoscale eddy field. Only when these key processes are resolved, rather than parameterized, can the estimates of the present state of the climate and its future possible evolution be significantly improved.

6. Conclusions

The ESMF is a landmark 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.

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