PROPOSAL COVER PAGE

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Proposal Title: A High-Performance Software Framework and Interoperable Applications for the Rapid Advancement of Earth System Science Part I: Core Earth System Modeling Framework Development

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NOTE: A number of Co-Investigators have changed since this proposal was first submitted in Nov. 2000

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Contents

(I) Science, Technology and Management

1 Introduction

This is one of three linked proposals to construct an Earth System Modeling Framework (ESMF) and implement using it high performance, interoperable codes for weather prediction, climate simulation, and data assimilation. This proposal (Part I) addresses core development of the ESMF. Part II focuses on implementing modeling applications using ESMF and Part III on implementing data assimilation applications. The institutions proposing this work are the NSF National Center for Atmospheric Research (NCAR), DOE Argonne National Laboratory (ANL), DOE Los Alamos National Laboratory, Massachusetts Institute of Technology (MIT), NASA Goddard Space Flight Center Data Assimilation Office (DAO) and NASA Seasonal to Interannual Prediction Project (NSIPP), University of Michigan, NOAA Geophysical Fluid Dynamics Laboratory (GFDL) and NOAA National Centers for Environmental Prediction (NCEP).

The ESMF is a concerted response to several current challenges in science and technology: the growing scientific complexity of Earth system models and larger collaborative communities, the increased demand for improved weather and climate prediction capabilities, and the challenge of developing applications in a volatile computing environment. The ESMF will address the technical aspects of these issues, laying the groundwork for addressing the more difficult scientific aspects, such as the physical compatibility of components, in the future.

The ESMF will consist of a *superstructure* for coupling and exchanging data between component models (e.g., atmosphere, ocean) and model subcomponents (e.g., physics, dynamics); and an *infrastructure* consisting of data structures for representing grids and fields and an optimized, portable set of low-level utilities. The data constructs and low-level utilities will be used by the coupling superstructure and may also be used separately to compose scientific applications. Thus our work will promote software reuse as well as interoperability. A unique feature of our design is an integrated approach to data assimilation. The ESMF will be designed in an object-oriented, layered manner to isolate machine dependencies, and to offer an application programming interface natural for the Earth sciences.

The "critical mass" of institutions participating in this proposal has also been active in the Common Modeling Infrastructure Working Group (CMIWG). For the past two years, this group has explored ways of enhancing collaborative Earth system model development. The CMIWG has attracted broad participation from major weather and climate modeling groups in research and operational centers. At a CMIWG workshop in February 2000, the core group of scientific CoIs on this proposal committed to developing a coordinated response to this CAN. Since then, working with computer scientists and software engineers, the group has established requirements and a preliminary design for a common framework. Several of our CoIs are also key participants in the Accelerated Climate Prediction Initiative (ACPI) Avante Garde project, a broadly based DOE-centered effort focused on restructuring the coupling and atmospheric component of the NCAR Community Climate System Model (CCSM). This work will be coordinated with ESMF development. Multi-agency and multi-institutional alliances of the sort represented by the CMIWG and collaboration on these ESMF proposals are a key recommendation of recent reports that discuss the deficiencies in our national climate modeling program [11, 34].

2 Scientific Objectives and Rationale

2.1 Objectives of the ESMF

One of the great strengths of atmospheric, oceanic and climate modeling in the U.S. is the variety, availability and wide use of models. But this diversity has also led to duplication of effort, a proliferation of models and codes which, due largely to technical reasons, cannot interoperate and have been unable to keep up and exploit advances in computing technology.

The specific objectives of the ESMF are to 1) **Facilitate the exchange of scientific codes (interoperability)** so that researchers may more readily interface with smaller-scale, process modeling efforts and can share experience among diverse large-scale modeling efforts; 2) **Promote the reuse of standard, non-scientific software**, the development of which now accounts for a substantial fraction of the software development budgets in many institutions; 3) **Focus community resources** to deal with changes in computer architecture; 4) **Present the computer industry and computer scientists with a unified, well defined and well documented task** to address; 5) **Share the overhead costs** of the housekeeping aspects of software development, such as documentation; and 6) **Provide greater institutional continuity** to model development efforts, by distributing support for modeling infrastructure throughout the community.

2.2 Scientific Benefits

In this section we describe ways in which the ESMF will increase scientific productivity and encourage new research in a range of Earth science domains. These include climate modeling and general circulation modeling, numerical weather prediction, and data assimilation.

2.2.1 Climate Modeling and GCMs

The ESMF will provide ready-made solutions to standard climate model issues such as grid representation and transforms, utility software and high-level scheduling. Standard interfaces will help keep the diverse community of developers coordinated.

Climate models are increasingly being used to guide policy decisions. The predictive requirements are becoming more stringent and data assimilation a crucial issue. The demand for interoperability of climate model components has intensified as growing evidence of anthropogenic climate change has focused scrutiny on the capabilities of the current generation of climate models. Without exchangeable model components, it is often difficult to point to a particular component as a clearly identifiable cause of divergent results when one model is compared against another or against the observations. The ESMF will facilitate just this sort of analysis.

The computational demands of coupled climate models necessitate the use of scalable parallel computational platforms. To effectively utilize such platforms codes must be based on flexible data structures and communication libraries that are performance portable. The ESMF will provide this infrastructure.

The most resource-intensive components of climate models are typically oceanic and atmospheric general circulation models (GCMs). Within a GCM physics and dynamics can be treated as separate coupled components themselves. This allows researchers to readily exchange dynamical cores, thus offering the opportunity to explore more efficient algorithms. NSIPP and GFDL models are already structured this way using the GEMS [29] and FMS [16] frameworks, respectively. Plug-compatible dynamical cores for the the atmospheric portion of the NCAR CCSM are under development.

The climate models that will be implemented using the ESMF in Part II are the NCAR CCSM [9], the MIT general circulation model (MITgcm) [18], and climate models implemented under the GFDL FMS and the NSIPP GEMS frameworks.

2.2.2 Numerical Weather Prediction

Operational forecasting centers have strict requirements for performance and reliability. By specifically optimizing parts of the ESMF, some of the hand-tuning optimization burden at operational centers can be shared with the rest of the modeling commmunity. Also, sharing utility code for error and signal handling, and having the whole community develop and test code, will contribute to the robustness of code overall.

The forecasting code we will use as a testbed for ESMF is the NCEP atmospheric global forecast code [21, 22, 23, 39]. It is a key component of the NCEP Global Data Assimilation System (GDAS) that provides the backbone of all numerical weather prediction at NCEP. It also is used to make the 4 times per day 120-hour Aviation forecast, the daily 384-hour Medium Range forecast and the 22 times per day 384-hour Ensemble forecasts at NCEP.

2.2.3 Data Assimilation

As in the modeling community, analysis software for data assimilation systems has been largely developed in isolation, making it difficult for groups to take advantage of activities taking place outside their home institutions. Transition of assimilation technology to the rigorous, stable standards of the operational environment is particularly challenging. The interoperability afforded by ESMF will enable the sharing of high level components such as on-line quality control systems, minimization algorithms and management of observational databases.

The data assimilation applications that will be implemented using ESMF in Part III span a variety of dynamical models and assimilation algorithms. Two different global 3D-VAR atmospheric data assimilation systems used operationally at the NASA DAO and NCEP [13, 14, 25, 31] will be implemented under ESMF, affording a great degree of interoperability between the two centers. Ocean products are only now emerging into the quasi-operational arena, so the inclusion of ocean state estimation tools within the same framework as atmospheric state estimation tools will be beneficial to speed development, portability, and interoperability. Two ocean data assimilation systems from NSIPP, the optimal interpolation and the Ensemble Kalman filter [28], will be implemented under the ESMF, as will a complementary approach from MIT. The MIT effort will develop the infrastructure under ESMF for 4D-VAR ocean data assimilation using the MITgcm and their tangent-linear and adjoint model compiler [17].

2.3 Community Delivery

The ESMF will be developed by and delivered immediately to a significant portion of the U.S. climate, weather prediction and data assimilation communities, and will be superbly positioned to migrate to closely related disciplines.

The variety of groups, institutions and disciplines that will implement applications using ESMF in this proposal set constitutes delivery to a "critical mass" of the U.S. climate and weather prediction communities. Our Investigator Team includes representatives of all the relevant disciplines and this proposal has the endorsements of the CMIWG leadership and most major modeling and data assimilation centers in the country. These groups include the following: the NASA/GSFC *DAO* and *NSIPP*, both central to NASA's mission to support data acquisition, dissemination, analysis and assimilation into models; *GFDL*, one of the world's leading academic and climate modeling centers; *MIT*, with expertise in model development, adjoint modeling, and innovative cluster technologies; *NCAR*, the internationally renowned climate modeling and research center, and home to the extensively used CCSM; and *NCEP*, the primary numerical weather prediction center in the US, with vast experience in the development of models and data assimilation systems.

Many Earth science application developers will adopt ESMF through relation to our Investigators' activities. This includes additional groups at participating insitutions, potential collaborators who wish to interoperate with our applications, and groups active in the CMIWG. The NCAR CCSM model alone offers several key mechanisms for wider community support. We will promote the ESMF at the yearly CCSM workshop, a widely attended, international forum for the discussion of climate issues. The CCSM is also the testbed for the DOE/NCAR ACPI Avante Garde project, a current effort to restructure the atmospheric component and coupling tools of the CCSM for greater efficiency and modularity. In addition to several of the institutions represented on this proposal, the ACPI project includes researchers and computer scientists from Oak Ridge National Laboratory, Lawrence Livermore National Laboratory, and Lawrence Berkeley Laboratory. We have been coordinating our ESMF effort with them closely and will continue to do so, through Investigators who are participating in both ACPI and this proposal (Boville, Jones, DeLuca, Larson).

Investigators Stout, DeLuca and Killeen are key participants in several space weather community efforts to construct a space weather modeling framework that will leverage the ESMF. Compatible Earth/space frameworks will facilitate projects such as the University of Michigan NSF Knowledge and Distributed Intelligence (KDI) project [12], which is combining space weather models with Earth system models to study Sun-Earth interactions.

The ESMF effort will draw in varied groups who are already using framework-friendly design strategies and may wish to influence and leverage our work. For example, there are likely to be opportunities for the ESMF activity to interact with a group at Colorado State University developing a modular Terrestrial Carbon Model under the NSF Integrated Research Challenges Program.

Anyone with an interest in Earth system modeling will have access to the ESMF source code and documentation via the web. We will encourage moderated open source development after a prototype version of the ESMF has been released.

We are investigating the possibility of expanding the CMIWG website, which includes a software repository for plug-in column physics parameterizations, to include ESMF distribution and a repository of scientific components for Earth system modeling.

A workshop is planned at the end of the proposed work to NASA to introduce the ESMF to a broad community. NCAR has committed to an ongoing support role for ESMF that will include the coordination of regular community workshops.

Finally, *we plan to present our work at conferences and publish our experiences and results in technical and Earth science journals.*

3 Technical Plan

The community collaborating on this proposal has already made significant progress in defining the structure of the ESMF. In August 2000, participating groups met at NCAR to review strawman documents each had prepared describing their application requirements, an ESMF scope and architecture, and implementation strategies
(see http://www.scd.ucar.edu/css/NASACAN.htm). Here we describe our preliminary conclusions: the appropriate scope, design and implementation of the ESMF.

3.1 ESMF Functionality

3.1.1 Scope

The scope of the initial ESMF addresses two critical needs: 1) robust, optimized, non-scientific *infrastructure* libraries with which to build models and model subcomponents and 2) a *superstructure* for coupling scientific components. The first of these promotes code reuse, the second, interoperability. GUIs, optimized math libraries for purposes other than regridding, and differential operators are secondary needs and are *not* part of the initial ESMF proposed here. These functions can be introduced to the ESMF in the future.

The coupling superstructure will perform highly optimized regridding, interpolation and communication of gridded, distributed data. The data may represent multiple fields or a single field, may be in the same or different executables, may be in code segments executing serially or concurrently, and may be distributed among nodes and/or partitioned among multiple threads. The interfaces for components and couplers must be natural for our problem domain.

The software necessary to support the above capabilities includes infrastructure for describing a wide variety of grids and decompositions, and for performing high-level manipulations of fields discretized on those grids. The software for specifying decompositions will interface to a mechanism for performing dynamic load balancing. Operations on grids and fields must implement corresponding methods for the construction of tangent linear and adjoint models.

Both the coupling mechanism and application codes will use common utility routines. ESMF utilities will include communication libraries, I/O, performance profiling, time management, and signal and error handling.

3.1.2 Requirements

In addition to achieving the critical ESMF goals of code interoperability and reuse, the ESMF software will conform to a set of functional requirements. These include:

Performance portability. Portability and computational efficiency over a wide range of platforms are essential. Optimized performance on scalable architectures for moderate numbers of processors (16-500) is the highest priority.

Flexible usage. The application writer must be able to choose how much or how little of the ESMF to use. For example, some application developers may want to use ESMF for coupling models while others may want to build component models using lower-level tools provided by ESMF.

Ease of use. The ESMF must adopt a straightforward approach to implementing our large and complex codes using the framework, and must have a natural interface for our problem domain.

Extensive grid support. ESMF must be able to couple components that are discretized on: logically rectangular grids (including bipolar and cubed-sphere grids); reduced (cut-out or Kurihara) grids; unstructured grids; phase space grids (e.g., spectral, Fourier); nested and adaptive grids; and icosahedral grids. It must be simple to add additional grids. We also require support for describing lateral grid boundaries, masked regions and halo regions.

High performance, extensible, multi-format I/O. The ESMF utilities must support a generic interface for I/O of self-describing data in netCDF, binary, GRIB, BUFR and EOS HDF data formats. There must be support for high-performance parallel I/O.

Multiple language bindings. ESMF utility and coupling software must be usable by applications written in C/C++ and F77/F90.

Other requirements. These include robust error and signal handling, runtime configurability, and an efficient, low maintenance implementation (e.g., auto-documentation from code).

3.2 Architecture

We begin by describing our strategies for achieving the major design goals of the ESMF: interoperability, reuse, performance portability and ease of use. An object-oriented design (OOD) [38] and software layering are our basic tools.

3.2.1 Strategy for Code Reuse and Interoperability

OOD enhances code **reuse** since the class structure encourages well-defined, general purpose, encapsulated code segments that can work in a variety of contexts. Both ESMF parallel utility classes and ESMF procedural system-level utilities will be used repeatedly in a variety of more complex classes in the framework and can also be used to compose many scientific applications. We will follow the model of the NWChem/ECCE [30] framework, which offers a useful separate toolkit.

We are concerned with several levels of **interoperability** in ESMF. The most fundamental level involves rewriting Earth science applications in a modular manner, and defining a standard interface for coupling based on the constructs and terminology natural for our problem domain.

We will address this level of interoperability by building the "inheritance" feature of OOD into the ESMF design. Classes that inherit a core set of attributes and operations can be queried and can communicate with other classes in a standard way. A second key feature of OOD is polymorphism, the ability to create a variety of interfaces and implementations for the same operation. This enables different classes with related functions to be handled generically. Together polymorphism and inheritance promote interoperability (see [15]). We note that inheritance and polymorphism can be implemented in C, C++ or F90, with varying ease.

In practice, certain classes within an application will be supplied by the ESMF and others (mainly scientific components) will be customized by the application developer. For example, an ocean model component of a climate model might need to contain a "getGrid" method that returns a description of its data grid and distribution. However, this method might not have the same arguments as a method returning equivalent information from a land model component (polymorphism). Coupling tools supplied by ESMF would call the "getGrid" method to understand how data should be routed to and from each type of component.

A secondary level of interoperability is the purely mechanistic issue of language compatibility. There are many options for handling this. First, using pointers to pass "opaque" data structures across language boundaries, and relying on accessor methods to return information about those data structures, is common in C-based packages (e.g. netCDF [35], PETSc [8]) Second, calling Fortran routines from C++ frameworks in order to use high-performance numerical kernels is standard practice (e.g. SAMRAI [19], KeLP [7], DAGH [27], others). Here the C++ data structures typically do not extend into the Fortran code. Climate and weather codes can be structured for this type of interoperability; for example, the Weather Research and Forecast Model (WRF) [26] has a "mediation" layer that breaks down data structures from a top-level "driver" layer and passes the decomposed information to a high-performance "model" or kernel layer. A third option is executing components via an interoperability environment, such as CCA [5] or Cactus [4]. Here multi-language components utilize a new, common language or mechanism such as CCA's Scientific Interface Definition Language (SIDL) in order to interoperate in a very generic environment. CCA is the most appealing mechanism of this type since it is being developed by a very large community as a standard.

We intend to study the strategies above and others further and present the work in an Implementation Report that will extend the work already done by the "ESS Integrator." The study will include prototyping key ESMF functions using different approaches to see if there are significant efficiency, ease of use, or other factors, as well as addressing issues such as compiler quality, utilization of existing staff, and ease of hiring new staff.

A third type of interoperability is the ease with which a given framework or toolkit can combine with others. We cite the excellent example of PETSc, co-developed by CoI Smith, which interoperates efficiently with a multitude of other packages. This is accomplished largely through careful treatment of data as it is brought into PETSc and an interface that makes minimal demands on the user, both of which we regard as sensible strategies.

3.2.2 Strategy for Performance Portability and Ease of Use

We will achieve performance portability and ease of use by layering code and by using generic, carefully designed interfaces.

Like object classes, layers help to organize code, though at a larger scale. The ESMF software will consist of five distinct software layers, each with well-defined functions and interfaces. The "lowest" layers are non-scientific and general in function. The "highest" layers describe functions that are more specific to the Earth system domain. Methods in higher layers call methods from lower layers, and classes in higher layers are often composites of classes found in lower layers.

Machine-dependent code will be isolated to the lowest level in the framework by wrapping it in a generic interface. This improves performance portability by reducing the scope of changes that need to be made to run on or optimize for a new architecture, and allowing us to optimize primitive operations by using vendor-specific libraries.

Likewise, calls to higher-level communication functions such as transposes are isolated to a layer in the framework so that an application developer does not need to manage the details of distributed data transfers. This makes the application code easier to write and use.

3.2.3 Preliminary Design

We describe here a layered ESMF architecture that will fulfill the requirements laid out in Section 3.1.2. A complementary description of ESMF functionality from an application developer's viewpoint is provided in Part II. The Part II ESMF description focuses on the data transformations necessary to support modeling applications. In this Section we focus on the structure of the framework itself.

The five layers in the ESMF architecture are shown in Figure 1. Since the middle three layers are closely related, we cluster them together and refer to them collectively as "Fields and Grids."

At the bottom are **low-level utilities**. These may be machine-dependent and may be coded procedurally for efficiency. Some examples of functions provided in this layer include: calendar management and alarms, lightweight performance profiling, and methods to support disk I/O. It is essential that these utilities be easily usable to compose applications independently.

The second layer is a set of **parallel utility classes**. This layer includes a retrievable description of a *machine model*, and a *layout* class that specifies the portion of the machine model over which a data object is distributed. An example of a method in this layer is the specification of a simple topology for a given layout.

Classes representing **distributed grids** are in the third layer, which contains a substantial portion of the ESMF. Distributed grids contain a layout that describes the grid decomposition, and a grid specification that describes the grid coordinates and connectivity. The methods here include *index-space* and *physical-space* methods. Examples of index-space methods include data transposes on logically rectilinear grids. Physical-space methods are those which additionally require knowledge of the spatial metric of the distributed grid: these include more complex regridding methods, such as computation of grid overlaps.

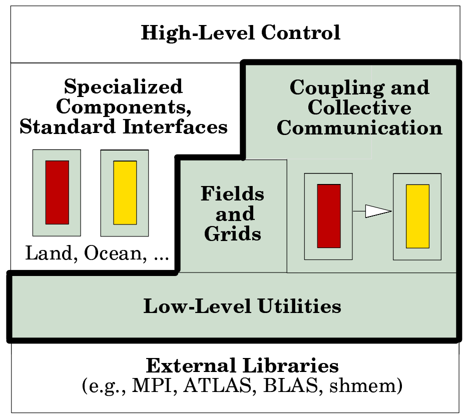
Fields are in the fourth layer. Fields contain a distributed grid and a field specification that describe attributes related to the physical field ("metadata"). We will also support a *field set* class, for fields that are discretized on the same distributed grid, since this is often the form of data communicated between model components. Operations in this layer will include using field metadata information to write header information for the self-describing data formats of Section 3.1.2.

The **coupling and components** layer includes large scale components, such as atmosphere and land models, and the classes used to simplify the transfer of data between them; for example, *boundary state vector* classes that comprehensively describe the portion of a component model state that is necessary for coupling. This layer also includes high-level control interfaces for scheduling different modes of component execution.

Figure 1: ESMF Layered Architecture

Components and Coupling		gridded component interface collective data transfers collective I/O
Fields and Grids	**Fields**	fields and field sets field description/metadata field I/O
	Grids	grid description/metadata grid decomposition
	Parallel Utilities	parallel utilities (halo...) machine layout
Low-Level Utilities		event alarms I/O primitives memory management signal and error handling performance profiling machine primitives

Figure 2: ESMF Application Architecture



We show the application developer's view of the ESMF in Figure 2. The figure includes both numerical components and core framework software, shaded grey, which is used by the components. Components operate under the direction of a high-level control program, whose role is to orchestrate a sequence of computation.

3.3 Framework Development Plan

ESMF development will involve intensive interaction between a core Implementation Team located at NCAR and a dispersed set of Earth scientists, computer scientists and software engineers located at collaborating institutions. Together these participants will define an *open standard* for ESMF software component interfaces - an evolving standard that will be open to members of our entire community to extend. The evolution of the standard from an interface design into a production-quality software package by the Implementation Team is the bulk of the work in this Part I proposal.

Early on in the project the Implementation Team will undertake a number of preparatory activities. They will work with application developers to create a validation suite from representative codes; they will collaborate closely with computer science CoIs and the ESMF Integrator to perform an implementation study (see Section 3.2.1); and they will begin work on creating a set of low-level utilities so that these can be used in the development of more complex classes.

Development on the core ESMF will proceed as detailed in the Software Engineering Plan. An appropriate sequence for class development will be identified and documented. As classes are completed and unit tested, they will be integrated into an evolving prototype of the ESMF. This work will be accompanied by efforts on the part of application developers to incorporate preliminary prototypes of the ESMF into their codes. We plan to use the existing frameworks GEMS and FMS to assist with rapid prototyping of implementation strategies. As the ESMF itself is implemented, both the application groups and Implementation Team will coordinate with the ESS Evaluation Team to undertake exhaustive testing and performance studies and will communicate their results to the wider community.

3.4 Test Application: the ESMF Validation Suite

The application that this Part I proposal will focus on is a synthetic ESMF VAlidation Suite (EVA) consisting of a set of representative segments from the Earth system codes described in detail in Parts II and III. EVA will evolve, be maintained, and be distributed with the framework, and will provide a straightforward way for developers and eventually installation sites to test and assess it. It will also serve as a focus to engage the computational science research community to boost the performance and scalability of our codes.

EVA performance and functionality will be baselined using the ESS Testbed (**Milestone E**). The metrics will be time to solution, scalability, and functionality in several areas: mode of execution (SPMD/MPMD), number of distributed grid types supporting optimized operations, an integrated hybrid (distributed/multithreaded) programming model, and support for C++ and F90 components. These metrics reflect both practical performance issues and an awareness of current trends. **Milestone F** focuses on functionality while **Milestone G** focuses on performance and scalability; this is consistent with the standard software engineering practice of "get it right before you make it faster," see for example [37]. The interoperability of EVA codes with the application codes in Parts II and III will be demonstrated in **Milestones I and J**. We will run on a variety of platforms throughout development, and the portability of the ESMF and EVA will be verified in **Milestone K**.

Composition of the Validation Suite

Based on the prototype framework design presented in Section 3.2.3, and initial dialogue among our Investigator Team we anticipate developing a suite organized into the following sub-areas:

Synthetic Components. Test components such as stand-alone solvers for Helmholtz problems, simple shallow water models, and standalone river runoff simulations have proven useful at GFDL, MIT and GSFC, and will be included in EVA. The set of synthetic components will be instrumented to allow performance and correctness to be evaluated rapidly. The components will test parallel primitive operations, including exploring the performance of primitives bound to different software and hardware technologies (e.g., IPC, Quadrics, Myrinet). The components will also serve to refine an ESMF machine model that can map efficiently to the diverse mix of parallel machine architectures the ESMF will target. We will use preliminary EVA components to test language interoperability options as part of the implementation study described in Section 3.5.2.

Synthetic Drivers. The test suite will also include a number of EVA drivers to test framework support and compatibility with different modes of execution (SPMD/MPMD executables; sequential/concurrent sequencing). The synthetic driver tests will verify that the framework works reliably in all of these cases.

Synthetic Couplers Tests using synthetic EVA couplers will check correctness and the performance and scaling of the ESMF interpolation and regridding tools. The EVA suite will validate treatment of aspects of Earth science component coupling such as subgrid scale variations, ungridded observational network datasets, and enforcing global conservation constraints. We will also create test codes that exercise the framework support for temporal accumulation and averaging. These tests will provide clear examples of how a component interfaces with a coupler.

Interoperability Tests Other framework functions that support interoperability will also be tested with the EVA couplers. These functions include mechanisms to allow one component to query parameters of another component, mechanisms to manage the representation of time and notification of periodic events within components in a standard way, and mechanisms to coordinate synchronized termination and subsequent resumption of multi-component, multi-CPU experiments. This work will also validate interoperation with software external to the framework.

3.5 Implementation Strategy

3.5.1 Use of Existing Tools and Frameworks

Frameworks with a significant subset of the capabilities desired for ESMF have been co-developed by members of our Investigator Team (FMS, GEMS, STAPL). Each of these offers support for data parallelism within components plus a higher level of large-scale task parallelism for coupling components. Each of these also offers a set of data constructs and general utilities. STAPL is a C-based framework for composing radar applications consisting of multiple subsystems; it is notable for its hybrid programming paradigm and real-time performance. FMS, from GFDL, and GEMS, from NSIPP, are modular, F90-based frameworks developed for use within GCMs and for coupled climate modeling. They have achieved institutional support and are relied on for production modeling. However, they do not have all the flexibility sought by the broader Earth science community, as identified in the goals and requirements laid out for the ESMF. Specifically, these systems lack: a hybrid programming model (see Section 3.5.2); the ability to represent and perform efficient data transfers on nested grids; highly optimized regridding (especially for unstructured grids); the ability to couple multiple executables; integrated error and signal handling for complex multiple-executable applications; and extensive multi-language support.

The coupling capabilities of FMS and GEMS are being extended in the CCSM Next Generation Coupler (NGC), part of the current NCAR/DOE ACPI effort that involves several of our CoIs (see Section 2.3). The NGC will include optimized regridding for a wide range of grids and a SPMD/MPMD option.

It is tempting to consider using one of the tools or frameworks described above as the basis for the ESMF. However, we feel strongly that the ESMF standard should be a community effort. ESMF will represent a powerful synthesis of what we have learned from these previous projects.

Members of our collaboration have also investigated other frameworks, such as POOMA [36], Overture [10], and Cactus [4].

Much of the functionality in the C++-based POOMA and Overture packages lies in fine-grained mathematical operations. We find these frameworks inappropriate models for ESMF since data parallelism is inefficient for many of our multi-component applications, and by writing application codes in Fortran or C we retain good performance.

The term “framework” can also refer to an effort such as the CCA project or Cactus, which provide tools for component coupling and language interoperability. These tools may be useful for ESMF. However, language interoperability is a relatively minor aspect of the interoperability we are concerned with, and there are alternative solutions which may be more appropriate (see Section 3.2.1).

We find that none of the frameworks we have examined are focused on our central needs, as described in Section 3.1.1. Therefore we would seriously question whether trying to modify an existing framework would benefit us more than adapting its more useful features into a wholly new ESMF implementation. Also, while we recognize the advantages of leveraging code from other groups, we feel that it is essential that the Earth system commmunity assume significant control over the framework that our codes are built on. We cite as cautionary examples cases of frameworks that attempted to be general for whom support has largely vanished, such as POET [6] and POOMA. It seems that the more successful frameworks and problem solving environments (for example, the NWChem/ECCE effort) are those that are quite domain specific and are developed and maintained by their own user communities. The success of existing framework efforts within our community, such as GEMS and FMS, indicates that this approach is both possible and appropriate.

We have identified a multitude of low-level utilities that could be extended or directly incorporated into the ESMF, such as documentation generators, timing libraries, and communication libraries. The SCRIP [20] package for conservative regridding, developed by CoI Jones, is especially relevant to our work. We are very open to investigating other packages.

3.5.2 Implementation Issues

Language: We anticipate implementing the low-level utilities of the framework mainly in C. An implementation study at the beginning of the proposed work will help to assess alternative approaches to developing upper levels of the framework (see Section 3.2.1.

Microprocessor architectures: Many of the climate and weather prediction codes in use today were developed for platforms based on vector processors rather than the dominant microprocessor-based architectures. The optimization strategies for these platforms can be radically different. A charge of the ESMF will be to make it easier for developers to obtain better performance on these platforms without changing significant amounts of application code.

Hybrid programming strategy: Clusters of shared memory systems are an increasingly prevalent platform, and the current trend is towards more processors per chip and per node. Including in ESMF a well-integrated capability to distribute data over nodes and computation over threads will position the framework to adapt to a range of future architectures.

3.6 Expertise in Scalable Grand Challenge Applications

Currently all participating institutions have highly optimized parallel implementations of at least some of their production codes. Figure 3 shows speed-up curves for a sampling of these applications. These were chosen to highlight the breadth of applications and platforms being used. Shown in the figure are results for both atmospheric (NCEP, NSIPP, CCM) and ocean (POP) models. Two of the models are spectral and two grid point; two are operational codes (NCEP and NSIPP) and two are research codes (CCM and POP). We show results on platforms from four of the leading U.S. manufactures: SGI, Cray, IBM, and Compaq. Most of these models, however, run on multiple platforms. Additional results appear in Parts II and III.

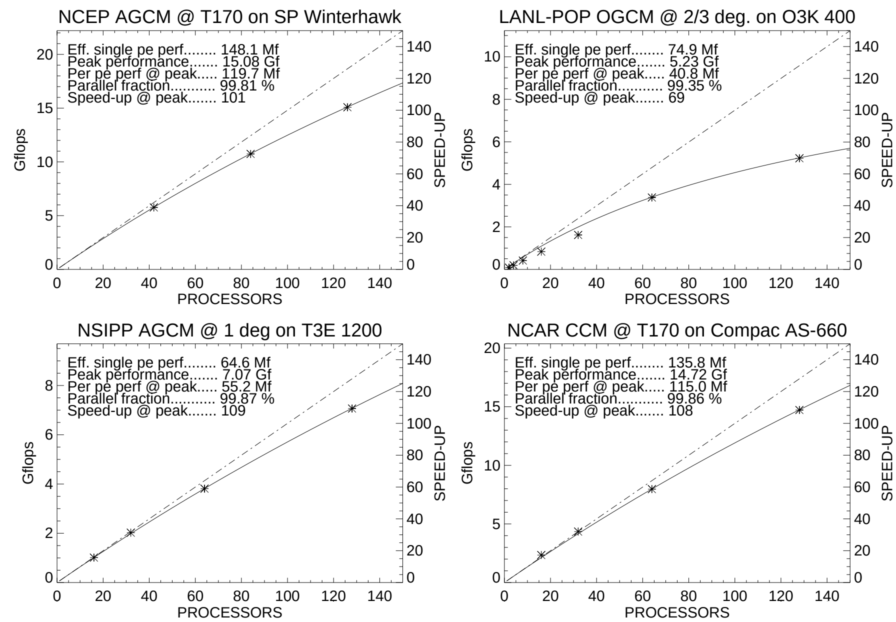


Figure 3: Speedup curves.

3.7 Vendor Participation

IBM, Cray Research, Sun Microsystems, Api Networks, and High Performance Technologies have expressed interest in partnering with us on the development of the ESMF by participating in design reviews, code reviews, and benchmarking.

4 Management Plan

4.1 Management Strategy

The key challenge in creating a management plan for the ESMF is to entrain broad expertise in the framework's development while ensuring that work can proceed efficiently, and that decisions can be made in an unambiguous manner. In order to accomplish this we will: 1) engage a broad spectrum of the Earth system modeling community in the specification of requirements and the overall design of the framework, maximizing expert input and user buy-in; 2) utilize groups with more focused interests to oversee the design and implementation of specific framework components in order to achieve timely, informed decisions; 3) delegate much of the work of design drafts, prototyping and production coding to a closely integrated, central team of software engineers; and 4) resolve inconsistencies and differences of opinion throughout the project by allowing final software engineering decisions to be made by a central software manager and selected "Oversight Team" leaders.

4.2 Investigator Team

The Principal Investigator of the proposal is **Tim Killeen**, the Director of NCAR.

The CoInvestigators are:

Ants Leetmaa, Director, NOAA Geophysical Fluid Dynamics Laboratory; **Byron Boville**, Senior Scientist and Head, Climate Modeling Section, NCAR; **Arlindo da Silva**, Meteorologist, Data Assimilation Office, NASA/GSFC; **Cecelia DeLuca**, Software Engineer, Scientific Computing Division, NCAR; **Roberta Johnson**, Director of Education and Outreach, University Corporation for Atmospheric Research; **Philip Jones**, Staff Member, Theoretical Fluid Dynamics Group at Los Alamos National Laboratory; **J. Walter Larson**, Assistant Computer Scientist, Mathematics and Computer Science Division, Argonne National Laboratory; **Stephen Lord**, Director, Environmental Modeling Center, National Centers for Environmental Prediction; **John Marshall**, Professor of Atmospheric and Oceanic Sciences, Massachusetts Institute of Technology; **Barry Smith**, Computer Scientist, Mathematics and Computer Science Division, Argonne National Laboratory; **Quentin Stout**, Professor, Computer Science and Engineering, University of Michigan; **Max Suarez**, NASA Seasonal to Interannual Prediction Project; NASA/GSFC.

The Investigator Team we have assembled possesses the required balance of scientific and computational expertise.

4.3 Management Structure and Implementation Team

As Principal Investigator, Dr. Killeen will serve as the primary contact and administrator of the proposed work. Dr. Killeen will negotiate agreements with NASA and among Investigator Team members, and will arrange for disbursement of funds after payment. He will supervise the overall activities of the Investigator Team and promote the ESMF project to the wider community. A software engineering manager (DeLuca) will oversee much of the day-to-day activity of the project.

Three *Oversight Teams* including the CoIs of the project will closely track and guide the design and implementation of the ESMF software. Each Oversight Team will consist of a mix of physical scientists, computer scientists, and software engineers, with some individuals on multiple Teams. The Oversight Teams correspond to different layers of the ESMF software (low-level utilities, fields and grids, coupling), and reflect different interests and expertise. For example, the Oversight Team for coupling will consist primarily of physical scientists, since the coupling layer contains the high-level interface that scientists will utilize when composing applications. Oversight Teams will remain in close contact with an *Implementation Team* located at NCAR through regular teleconferences and meetings. The Oversight Teams will participate in requirements analysis, design reviews, prototyping and testing over the course of the project.

The Implementation Team will consist of five software engineers hired specifically for the ESMF project, and a software engineering manager (DeLuca). One member of the Implementation Team will be an *integrator*, whose duties will include setting up the configuration management system and documenting procedures early in the project, and, once the project gets underway, assimilating newly developed classes and functions into an evolving prototype of the ESMF. The Implementation Team will also include *two software engineers with experience in OOD* and high-performance computing to implement the upper levels of the framework; *an application engineer* with mathematical and Earth system simulation experience who will begin assembling the validation suite immediately, and will serve as a primary interface to application developers at other institutions; and a *systems engineer*, to implement relatively straightforward utility functions.

We also request funds for a graduate student at the University of Michigan, to address issues in core ESMF development relevant to the space weather community; a research scientist at MIT, to assist with development of a variety of basic functions; and one-half FTE at Los Alamos to work on conservative regridding, building on the SCRIP package.

We propose to fund staff for core framework development partly through NSF cosponsorship and partly through NASA HPCC. Management positions, including the Principle Investigator and software engineering manager, will be funded through NSF cosponsorship.

4.4 Qualifications

Our Investigator Team possesses the combination of skills and backgrounds necessary to develop the ESMF and establish it as a standard throughout the climate and weather communities. The most critical of these skills are:

Expert understanding of the way in which Earth science applications and components are constructed and combined to support scientific research. The quality of the scientific expertise on our Team is demonstrated by the extensive publication lists, awards and honors, and prominent positions held by our scientific CoIs.

Previous experience creating and supporting parallel, high-performance software frameworks and toolkits for a large user community. Dr. Suarez was a co-developer of GEMS at NSIPP, a framework for climate and general circulation modeling. Ms. DeLuca was a co-developer of the parallel STAPL framework for real-time signal processing, a software tool currently used in multiple military radar systems. Dr. Boville was a co-developer of the CCSM, a model that is distributed to and supports hundreds of researchers internationally. Dr. Smith has been central in developing and providing ongoing support for the PETSc package for solving PDEs on parallel platforms, which has a user base in the hundreds.

Experience in technical management and development in a CMM Level II+ environment. Most of the Investigators in this project include technical management as part of their job. Ms. DeLuca served as the technical lead for new development on the STAPL framework project at MIT Lincoln Laboratory, a large, DoD-sponsored project that employed approximately 15 FTEs over the course of about 4 years, and was targeted at CMM Level III.

Proven skill in constructing algorithms and data structures to enable very high-performance codes. All of our investigators have experience constructing scalable, high-performance codes on parallel platforms; for example, Dr. Stout was a NASA HPCC Round II Participant in a space weather project that achieved 343 GFLOPS on 1490 processors of a Cray T3E-1200 for the MHD code BATS-R-US.

Extensive contacts to promote the ESMF. Established FMS and GEMS users at GFDL and NSIPP, respectively, are accustomed to working with a framework and will readily adapt to the ESMF. Hundreds of researchers will be introduced to the framework through their involvement with the NCAR CCSM. Finally, the involvement and advocacy of Dr. Killeen, Director of NCAR, and other internationally recognized scientists on our Investigator Team will help to generate interest in and support for our project.

(II) Software Engineering Plan

In this section we present a software engineering plan for the ESMF, including software team structure and management, a software process that extends from system specification through distribution and maintenance, and tools and techniques to support development, collaboration, and distribution.

1 Software Teams and Management

An *Implementation Team* will be established at NCAR consisting of five software engineers supervised by a *software engineering manager*. One of the software engineers will be an *integrator* (no relation to the NASA "ESMF Integrator") who is responsible for Team support functions such as configuration management and defect tracking. The Implementation Team will draft design specifications, prototype and implement ESMF components, test and validate the framework, and distribute releases. Software development will be guided by three partially overlapping *Oversight Teams* focused on different aspects of the framework: utilities, fields and grids, and coupling. The members of the Oversight Teams will include the CoIs of this proposal, and will consist of appropriate mixes of software engineers, application scientists and computer scientists. Each Oversight Team will designate a lead. Responsibilities of the Oversight Teams will include reviewing software design and tracking implementation progress.

The software engineering manager and integrator will maintain a system view and ensure that development is coordinated. The Oversight Teams and Implementation Team will coordinate with staff at other institutions working on applications for Parts II and III.

2 Software Process

The Implementation Team will follow a structured software process commensurate with CMM Level II [32, 33]. The process will include many of the procedures recommended by the Software Best Practices Initiative [3]. Our documents and reviews will be simplified versions of those described in standard references [24, 40, 41]. We will aim for an effective process free of extraneous overhead.

Staged Software Development The major milestones described in Part V are the result of the coordinated completion of many smaller events, each of which has a "completion gate," such as approval of a document. Table 1 shows the progression of events in ESMF software development, and the product and gate associated with each event.

The initial set of events, labelled "ESMF Definition" is focused on specifying the ESMF system and procedures as a whole. The second group of events, "Class Implementation" describes the development steps applied to individual software classes. As classes are completed they will be integrated into an evolving prototype of the ESMF. The final development stage, "Integration and Distribution", involves the integration of classes leading to a software release. The ESMF will have three major software releases corresponding to milestone I,J, and K; smaller releases and demonstrations will be scheduled to ensure that the project is on track.

Table 1 ESMF Software Event Progression

Event	*Product*	*Completion Gate*
ESMF DEFINITION		
Requirements specification Outlines ESMF functional scope and requirements.	Requirements Document *Prepared by:* all collaborators	Document review *Reviewed by:* all collaborators
Architectural description Describes layering strategy, function and interaction of major components.	Architecture Document *Prepared by:* all collaborators	Document review *Reviewed by:* all collaborators
Software process definition Evolving documentation describing software procedures.	Developer's Guide Document *Prepared by:* integrator	Document review *Reviewed by:* software mgr.
Implementation study Assesses existing software, optimal language, threading strategy, more.	Implementation Report *Prepared by:* implementation team	Document review *Reviewed by:* all collaborators
Software implementation and test plan Plan for Implementation and testing based on class dependencies, milestones.	Software Impl. and Test Plan *Prepared by:* software mgr.	Plan review *Reviewed by:* all collaborators
CLASS IMPLEMENTATION		
Class design Includes requirements, function, and interface specification.	Class Design Document *Prepared by:* class developer(s)	Design review *Reviewed by:* Oversight Team, software mgr.
Class implementation A class may be stubbed or partially implemented for a given release.	Prototype code *Prepared by:* class developer(s)	Code review *Reviewed by:* Oversight Team, software mgr.
Class unit test Class is tested stand-alone with a variety of inputs.	Unit test code *Prepared and tested by:* class developer(s)	Unit test *Verified by:* software mgr.
INTEGRATION AND DISTRIBUTION		
Class integration Unit tested class is integrated into an evolving prototype of the ESMF.	ESMF system prototype *Prepared by:* class developer(s), integrator	System test and benchmarking *Verified by:* software mgr.
User documentation updated Class design documentation is updated and converted to user documentation.	User's Guide & Reference *Prepared by:* class developer(s), integrator	Review before software release *Reviewed by:* software mgr.
System release Code and documentation is released. Defects and requests for features are tracked and incorporated into future releases.	System test *Prepared by:* integrator, software mgr.	ESMF system release *Evaluated by:* ESS Project, user community

Documents, Reviews and Verification

Documents: Documents to be prepared for this project are outlined in Table 1. We will structure design documents so they can be easily converted to user documentation. All documents will be prepared in a format that easily generates both hardcopy and web-friendly html. We intend to use a documentation generation tool to automatically create and update portions of our documentation.

Reviews: As shown in Table 1, a variety of reviews will be held, including requirements, design and code reviews. The outcome of a review will either be a pass or, if significant changes are required, another review iteration. The software engineering manager will attend all reviews for coordination.

Verification and benchmarking: Class and system tests will be designed so that they verify that the code being tested fulfils its requirements. The validation suite to be developed is described in Section 3.4. The ESS Evaluation Team and vendors will assist with performance evaluation.

Source Availability and Distribution We plan to develop our code in an open source development environment such as SourceForge [2]. After a prototype is released, we plan to engage the broader Earth science community in contributing to the ESMF. Community contributions will be integrated into new releases by the core team at NCAR.

Source code and documentation will be distributed via an ESMF website. The website may be an extension of that currently maintained by the CMIWG, as noted in Section 2.3. We plan to hold a series of workshops to introduce the broader community to the ESMF.

Software Maintenance NCAR is committed to offering an ongoing program of user support, maintenance, promotion, and research into improved and extended capabilities for the ESMF. We plan to retain some or all members of the Implementation Team at NCAR as core staff to carry out this work.

NASA ESS Team Role We welcome coordination with NASA technical staff, and would anticipate detailing our interactions during the negotiation process.

3 Software Tools and Techniques

Configuration management: We will likely use CVS for configuration management since it is mature, freely available, and the current community standard. We anticipate maintaining code at the following acceptance levels: **Active** (untested), **Unit tested**, and **Integrated** (code is part of a working ESMF prototype). These levels reflect the completion gates applied to code development shown in Table 1.

Software metrics: The software engineering manager will track a simple set of software metrics throughout development to evaluate progress and predict schedules.

Defect tracking: A tool such as Bugzilla [1] will be used to maintain a database of defects and new feature requests.

Collaborative tools: We plan to employ weekly teleconferences to keep Oversight Teams in close touch with the Implementation Team, as well as quarterly face-to-face meetings. We will continue to maintain project mailing lists and discussion forums.

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(IV) Biographical Sketches

TIMOTHY L. KILLEEN

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PROFESSIONAL INTERESTS

My interests span the environmental and space sciences, collaboration science and technology, and undergraduate educational reform.

EDUCATION

B.Sc.	1972	1st Class Honors in Physics, University College, London
PhD.	1975	Atomic and Molecular Physics, University College, London

SELECTED HONORS AND AWARDS

1996-2000	President and President-Elect, American Geophysical Union, Space Physics and Aeronomy Section
2000	Excellence in Teaching Award, University of Michigan, College of Engineering
1998	NASA Achievement Award, Polar Spacecraft
1993	Excellence in Research Award, University of Michigan, College of Engineering

EMPLOYMENT

2000–Present	Director	National Center for Atmospheric Research
1997–2000	Associate Vice President for Research	University of Michigan
1997–2000	Director	Global Change Laboratory, University of Michigan
1993–1998	Director	Space Physics Research Laboratory, University of Michigan
1987–1990	Associate Professor	Atmospheric, Oceanic and Space Sciences University of Michigan
1984–1987	Associate Research Scientist	University of Michigan

SELECTED PUBLICATIONS

1. Burns, A.G., and T.L. Killeen, "Composition changes in the thermosphere: an overview," submitted to *J. Atmos. Sol. Terr. Phys.*, 1999.

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ANTS LEETMAA

NOAA/Geophysical Fluid Dynamics Laboratory,
P.O. Box 308,
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PROFESSIONAL INTERESTS

As Director of NOAA/Geophysical Fluid Dynamics Laboratory, I am interested in fostering the development of improved predictive capabilities of climate change and variability on interseasonal to centennial timescales, including the development of comprehensive Earth system modeling capabilities.

EDUCATION

B.S.	1965	Physics, University of Chicago
Ph.D.	1969	Oceanography, Massachusetts Institute of Technology

EMPLOYMENT

2001–Present	Director	NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ
1997–2001	Director	NWS/Climate Prediction Center, Washington, D.C.
1995–1997	Senior Scientist	NWS/Office of the Director, Washington, D.C.
1990–1995	Chief	NWS/Coupled Model Project, National Meteorological Center, Washington, D.C.
1986–1990	Supervisory Oceanographer	Climate Analysis Center, Washington, D.C.
1972–1986	Research/ Supervisory Oceanographer	Environmental Research Laboratories, Miami, Florida

HONORS AND AWARDS

NOAA - Bronze Medal, 1996
NOAA - Gold Medal, 1998
AMS - Special Award

SELECTED PUBLICATIONS

1. Ji, Ming, and A. Leetmaa "Impact of Data Assimilation on Ocean Initialization and El Nino Prediction," *Mon. Weath. Rev.*, **125**, 724-753, 1997.

2. Latif, M., et al, A. Leetmaa, "A Review of Predictability and Prediction of ENSO, *Journal of Geophysical Research*, **103**, 14375-14393, 1998.

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PROFESSIONAL INTERESTS

My research has concentrated on developing and applying general circulation models of the lower and middle atmosphere for studies of atmospheric dynamics and climate. I have been one of the central figures in both the scientific and computational development of 4 generations of the NCAR atmospheric general circulation model. More recently, I have concentrated on coupled ocean-atmosphere modeling and was co-chair of the team which developed the NCAR Climate System Model (CSM). I am currently interested in the climate impact of solar variability and the role of the middle atmosphere in climate variability and climate change.

EDUCATION

B.Sc.	1975	1st Class Honors in Meteorology, McGill University, Montreal, Canada
Ph.D.	1979	Atmospheric Sciences, University of Washington, Seattle, Washington

EMPLOYMENT

1999–Present	Head	Climate Modeling Section, Climate and Global Dynamics Division National Center for Atmospheric Research
1992–Present	Senior Scientist	National Center for Atmospheric Research
1981–1992	Scientist I-III	National Center for Atmospheric Research
1979–1981	Postdoc	Advanced Study Program National Center for Atmospheric Research

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CECELIA DeLUCA

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PROFESSIONAL INTERESTS

My interests include the design of large, high-performance software systems, particularly those relating to atmospheric science; parallel algorithms; real-time systems, and software engineering tools and processes. I was a design lead on the development of the Space-Time Adaptive Processing Library (STAPL) parallel framework for real-time radar applications. STAPL is an integral part of multiple operational next-generation radar systems and has been ported to several platforms. It extends the serial Vector Signal and Image Processing Library (VSIPL) standard to SMP-cluster architectures. Previous projects have included the development of parallel codes for the simulation of middle atmospheric dynamics, atmospheric chemistry, and remote sensing of atmospheric temperatures.

EDUCATION

A.L.B.	1992	Liberal Arts/Social Sciences, Harvard University, Cambridge, MA
M.S.	1994	General Engineering, Boston University, Boston, MA
M.S.	1996	Meteorology, Massachusetts Institute of Technology, Cambridge, MA

AWARDS

1994 Boston University College of Engineering Outstanding Achievement Award, first in graduating class

EMPLOYMENT

1999–Present	Software Engineer	Scientific Computing Division, National Center for Atmospheric Research
1998–1999	Lead Software Engineer	MIT Lincoln Laboratory
1996–1998	Software Engineer	MIT Lincoln Laboratory
1993–1994	Manager, Technical Support	Omnet Communications

SELECTED PUBLICATIONS

1. Dickinson, R.E., S.E. Zebiak, J.L. Anderson, M. Blackmon, C. DeLuca, T. Hogan, M. Iredell, M. Ji, R. Rood, M. Suarez, K. Taylor, "Need for Infrastructure and Commonality in Climate and Weather Prediction Codes and Data," submitted to *Bulletin of the American Meteorological Society*, 2000.

2. DeLuca, C., C. Heisey, R. Bond and J. Daly, " A Portable, Object-Based Parallel Library and Layered Framework for Real-Time Radar Signal Processing," In *Proceedings of Scientific Computing in Object-Oriented Parallel Environments*, ISCOPE 1997.

3. Heisey, C., C. Adamo, M. Arakawa, P. Baggeroer, J. Daly, C. DeLuca, W. Dale Hall, K. Pickard, and H. A. Spang, "Implementation of the STAP Library and Framework (STAPL) for Real-Time Matrix-Based Signal Processing," In *Abstracts of High Performance Embedded Computing*, HPEC 1998.

ARLINDO da SILVA

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PROFESSIONAL INTERESTS

My current research interests include techniques for global atmospheric data assimilation, physical-space analysis systems, error covariance modeling, bias estimation and correction, quality control, land-surface, precipitation and aerosol data assimilation, and efficient methods for assimilation of remotely sensed data. Other research interests not in the area of data assimilation include aerosol forcing of climate, hydrological cycle of the subtropics, estimation of fluxes of heat, momentum and fresh water over the global oceans for observational studies and forcing ocean models.

EDUCATION

B.S.	1982	Physics, Catholic University of Rio de Janeiro, Brazil
M.S.	1984	Physics, Catholic University of Rio de Janeiro, Brazil
Ph.D.	1989	Meteorology, Massachusetts Institute of Technology

EMPLOYMENT

1994–Present	Meteorologist	Data Assimilation Office, NASA Goddard Space Flight Center
1990–1993	Assistant Professor	University of Wisconsin-Milwaukee
1989–1990	Visiting Scientist	Program in Atmospheric and Ocean Sciences Princeton University

RELATED PUBLICATIONS

1. Guo, J., and A. da Silva, 1997: Computational aspects of Goddard's Physical-space Statispical Analysis System (PSAS). In *Numerical simulations in the environmental and earth sciences.*, Garcia et al., Eds., ISBN 052158047, Cambridge University Press, 1997.

2. Dee, D. and A. da Silva, 1998: Data assimilation in the presence of forecast bias. *Q. J. R. Meteor. Soc.*, **124**, 269-295.

3. Joiner, J. and A. da Silva, 1998: Efficient Methods to Assimilate Satellite Retrievals Based on Information Content. *Q. J. R. Met. Soc.*, **124**, 1669–1694.

4. Cohn, S. E., A. da Silva, J. Guo, M. Sienkiewicz, D. Lamich. 1998: Assessing the Effects of Data Selection with the DAO Physical-space Statistical Analysis System. *Mon. Wea. Rev.* . **126**, 2913-26.

5. Sawyer, W., L. Takacs, A. da Silva and P. Lyster, 1999: Parallel grid manipulations in earth science calculations. *Lecture Notes in Computer Science*, **1573**, 666-679. Springer, Berlin.

ROBERTA JOHNSON

National Center for Atmospheric Research,
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PROFESSIONAL INTERESTS

My research interests include modeling and analysis of aspects of the coupled magnetosphere/ionosphere/thermosphere system, paleoclimatology, isotope geochemistry and atmospheric chemistry, education, and multimedia.

EDUCATION

B.S	1980	Geophysics and Space Physics, University of California at Los Angeles
M.S.	1984	Geophysics and Space Physics, University of California at Los Angeles
M.S.	1987	Geophysics and Space Physics, University of California at Los Angeles

EMPLOYMENT

2000–Present	Director	Education and Outreach University Corporation for Atmospheric Research,
1993–2000	Associate Research Scientist	Space Physics Research Laboratory University of Michigan
1998–1999	Adjunct Associate Professor	Dept. Atmospheric, Oceanic and Space Science, University of Michigan
1989–1993	Assistant Research Scientist	Space Physics Research Laboratory, University of Michigan

SELECTED PUBLICATIONS

1. Johnson, R.M., C. Alexander, S. Barlett, M. Burek, T. Clarke, J. Durrance, J. Green, J. Kozyra, J. Linker, D. Mastie, P. Orselli, C. Rasmussen, R. Redding, and T. Weymouth, “Windows to the Universe,” *WebNet ’96*, Association for the Advancement of Computing in Education, ed. Hermann Maurer, 1996.

2. Azeem, S.M.I., T.L. Killeen, R.M. Johnson, Q. Wu, and D.A. Gell, “Space-time analysis of TIMED Doppler Interferometer (TIDI) measurements,” submitted to *Geophysical Research Letters*, 1999.

3. Azeem, S.M.I., Johnson, R.M., “Lower-Thermospheric Neutral Winds at Sondre Stromfjord: A Seasonal Analysis,” *JGR*, 102, 7379-7397, 1997.

4. Johnson, R.M. and J.G. Luhmann, “On the Dynamical Response of the High Latitude Mesopause to Solar Proton Events: Poker Flat MST Radar Observations and Results of a Simple Classical Tidal Model,” *Journal of Atmos. and Terr. Physics*, **55**:9, 1203-1218, 1993.

PHILIP W. JONES

Theoretical Fluid Dynamics (T-3),
Los Alamos National Laboratory,
Los Alamos, NM 87545

PROFESSIONAL INTERESTS

Current interests involve the use of massively parallel computers to study problems in geophysical and astrophysical fluid dynamics, including atmosphere, ocean and coupled climate modeling, middle atmosphere dynamics and fully-compressible thermal convection.

EDUCATION

B.S.	1985	Physics and Mathematics with distinction, Iowa State University
Ph.D.	1991	Astrophysical, Planetary, and Atmospheric Sciences, University of Colorado

EMPLOYMENT

1993–Present	Staff Member	Theoretical Fluid Dynamics (T-3), Los Alamos National Laboratory
1991–1993	Post-doctoral Research Associate	Geoanalysis Group (EES-5), Los Alamos National Laboratory
1986–1991	Research Assistant	Joint Institute for Laboratory Astrophysics and Center for Applied Parallel Processing, University of Colorado, Boulder

SELECTED PUBLICATIONS

1. Jones, P.W. 1999 "First- and Second-order Conservative Remapping Schemes for Grids in Spherical Coordinates," *Mon. Weath. Rev.*, **127**, 2204-2210.

2. Jones, P.W., Malone, R.C. and Lai, C.A. 1998 "The Los Alamos Coupled Model," *Proceeding of the Second International Workshop on Software Engineering and Code Design in Parallel Meteorological and Oceanographic Applications*, ed. M. O'Keefe and C. Kerr, NASA Publication GSFC/CP-1998-206860.

3. Jones, P.W. 1998 "The Los Alamos Parallel Ocean Program (POP) and Coupled Model on MPP and Clustered SMP Computers," *Making its Mark: Proceedings of the 7th ECMWF Workshop on the Use of Parallel Processors in Meteorology,* ed. G. R. Hoffmann and N. Kreitz (Singapore: World Scientific Publishing).

4. Jones, P.W., Hamilton, K.P. and Wilson, R.J. 1996 "A Very High-Resolution General Circulation Model Simulation of the Global Circulation in Austral Winter," *J. Atm. Sci.*, **54**, 1107-1116.

5. Jones, P.W., Kerr, C.L. and Hemler, R.S. 1995 "Practical Considerations in Development of a Parallel SKYHI General Circulation Model," *Parallel Computing,* **21**, 1677-1694.

J. WALTER LARSON

Mathematics and Computer Science Division,
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PROFESSIONAL INTERESTS

My interests include the design and development of modular, high-performance software for use in data assimilation, regional and global climate modeling, and statistical analysis of climate model output. In the past I have performed research in a number of areas, including: soliton theory; chaos and dynamical systems; global climate change; regional climate modeling.

EDUCATION

B.A	1984	Physics and Mathematics, Drake University, Des Moines, IA
M.S.	1986	Physics, College of William and Mary, Williamsburg, VA
PhD.	1992	Physics, College of William and Mary, Williamsburg, VA

EMPLOYMENT

1999–Present	Assistant Computer Scientist	Mathematics and Computer Science Division, Argonne National Laboratory
1996–1999	Research Associate	Meteorology Dept, University of Maryland and NASA Data Assimilation Office
1994–1996	Postdoctoral Fellow	Centre for Resource and Environmental Studies, Australian National University

SELECTED PUBLICATIONS

1. C. H. Q. Ding, P. M. Lyster, J. W. Larson, J. Guo, A. da Silva, “Atmospheric Data Assimilation on Distributed-Memory Parallel Computers,” in *International Conference and Exhibition on High-Performance Computing and Networking (HPCN Europe ’98)*, Springer-Verlag, Lecture Notes in Computer Science, (1998).

2. J. Guo, J. W. Larson, P. M. Lyster, and G. Gaspari, *Documentation of the Physical-space Statistical Analysis System (PSAS): The Factored Operator Error Covariance Model Formulation*, DAO Office Note 98-04, Data Assimilation Office, Goddard Space Flight Center, Greenbelt, MD 20771 (1998).

3. J. Larson, J. Guo, P. M. Lyster, and G. Gaspari, *Documentation of the Physical-space Statistical Analysis System (PSAS): The Software Implementation of the PSAS*, DAO Office Note 98-05, Data Assimilation Office, Goddard Space Flight Center, Greenbelt, MD 20771 (1998).

4. D. P. Dee, L. Rukhovets, R. Todling, A. M. da Silva, and J. W. Larson, ”An adaptive buddy check for observational quality control,” submitted to *Q. J. R. Meteorol. Soc.* (2000).

STEPHEN J. LORD

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National Centers for Environmental Prediction
NOAA Science Center, Rm. 207
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PROFESSIONAL INTERESTS

My interests are in managing and participating in all aspects of data assimilation and numerical model development for weather and seasonal climate forecasts. As Director of the Environmental Modeling Center, National Centers for Environmental Prediction, I oversee a staff of 90 who are dedicated to improving operational weather, ocean and climate modeling products to support the National Weather Service mission.

EDUCATION

B.S.	1969	Physics Yale University (cum laude)
M.S.	1975	Atmospheric Sciences University of California at Los Angeles
Ph.D.	1978	Atmospheric Sciences, University of California at Los Angeles

HONORS AND AWARDS

1997	AMS Fellow
1996	NOAA Dept. of Commerce Gold Medal for Implementation of the GFDL Hurricane Model
1993	NOAA Dept. of Commerce Bronze Medal for Applied research on hurricane track prediction

EMPLOYMENT

2000–Present	Director	Environmental Modeling Center, National Centers for Environmental Prediction
1993–2000	Acting Director/Deputy Director	Environmental Modeling Center, National Centers for Environmental Prediction
1989–1993	Meteorologist	National Meteorological Center
1980–1989	Meteorologist	Hurricane Research Division, Atlantic Oceanographic and Meteorological Laboratory

SELECTED PUBLICATIONS

1. Pu, Zhao-Xia, S.J. Lord, and E. Kalnay, 1998: Forecast sensitivity with dropsonde data and targeted observations. In press *(Tellus)*

2. Surgi, N., H.L. Pan, and S.J. Lord, 1998: Improvement of the NCEP global model over the tropics: an evaluation of model performance during the 1995 hurricane season. *Mon. Wea. Rev.*, 126, 1287-1305

3. Lord, S.J., and J. L. Franklin, 1990: The environment of Hurricane Debby (1982). Part II: Thermydynamic fields. *Mon. Wea. Rev.*, 118, 1444-1459.

4. Lord, S. J., and J. M. Lord, 1998: Vertical velocity structures in an axisymmetric, nonhydrostatic tropical cyclone model. *J. Atmos. Sci.*, 45, 1453-1461.

JOHN MARSHALL

Department of Earth, Atmospheric and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, MA 02139

PROFESSIONAL INTERESTS

My research is directed at understanding key components of the general circulation of the atmosphere and ocean and the development of models to study them. I am interested in a variety of problems in geophysical fluid dynamics and their role in climate, ranging from rotating convection, the global circulation of the ocean and air-sea interaction. I use and develop numerical models of the atmosphere, ocean and climate.

EDUCATION

B.S.	1976	First Class Honors in Physics, Imperial College, London
Ph.D.	1980	Physics Imperial College

EMPLOYMENT

1992–Present	Professor	Massachusetts Institute of Technology
1992	Associate Professor	Massachusetts Institute of Technology
1991–1992	Reader in Physics	Imperial College
1984–1990	Lecturer in Physics	Imperial College
1982–1983	Post-doctoral fellow	University of Oxford

SELECTED PUBLICATIONS

1. Marshall, J., C. Hill, L. Perelman, and A. Adcroft, (1997) Hydrostatic, quasi-hydrostatic, and nonhydrostatic ocean modeling, *J. Geophysical Res.*, 102(C3), 5733–5752.

2. Marshall, J., A. Adcroft, C. Hill, L. Perelman, and C. Heisey, (1997) A finite-volume, incompressible Navier Stokes model for studies of the ocean on parallel computers, *J. Geophysical Res.*, 102(C3), 5753–5766.

3. Adcroft, A.J., Hill, C.N. and J. Marshall, (1997) Representation of topography by shaved cells in a height coordinate ocean model, *Mon. Wea. Rev.*, 125, 2293–2315

4. Marshall, J., Jones, H. and C. Hill, (1998) Efficient ocean modeling using non-hydrostatic algorithms, *Journal of Marine Systems*, 18, 115–134

5. Shaw; A. Arvind, Cho, K.-C., Hill, C., Johnson, R.P. and Marshall, J. (1998) A comparison of implicitly parallel multi-threaded and data-parallel implementations of an ocean model based on the Navier-Stokes equations. *J. of Parallel and Distributed Computing*, **48**:1, 1–51

BARRY F. SMITH

Mathematics and Computer Science Division,
Argonne National Laboratory,
Argonne, IL 60439-4844

PROFESSIONAL INTERESTS

My research interests include parallel computing and the numerical solution of partial diffrential equations.

EDUCATION

B.S.	1986	Mathematics Yale University
Ph.D.	1990	Mathematics New York University

HONORS AND AWARDS

1993	Co-winner, Householder Prize for best dissertation in numerical linear algebra during the preceding
1991	Second Prize, Fifth Leslie Fox Prize Meeting, international prize in numerical analysis offered every
1990	First Prize, Student Paper Competition, Copper Mountain Conference on Iterative Methods

EMPLOYMENT

1995–Present	Computer Scientist	Mathematics and Computer Science Division, Argonne National Laboratory
1994–1995	Assistant Computer Scientist	Mathematics and Computer Science Division, Argonne National Laboratory
1992-1994	Assistant Professor (Visiting)	University of California at Los Angeles Argonne National Laboratory

SELECTED PUBLICATIONS

1. *On the Interaction of Architecture and Algorithm in the Domain-Based Parallelization of an Unstructured Grid Incompressible Flow Code*, D. K. Kaushik, D. E. Keyes and B. F. Smith, 1998, Proc. 10th Intl. Conf. on Domain Decomposition Methods, J. Mandel, et al, eds., Amer. Math. Soc., pp. 311–319.

2. Smith, B. An Interface for Efficient Vector Scatters and Gathers on Parallel Machines, Preprint ANL/MCS-P701-1197; submitted to *International Journal of High Speed Computing.*

3. Balay, S., W. Gropp, L. Curfman Mcinnes and B. Smith, "Efficient Management of Parallelism in Object-Oriented Numerical Software Libraries," In *Modern Software Tools in Scientific Computing*, E. Arge, A. M. Bruaset and H. P. Langtangen, Ed. Birkhauser Press, 1997. pp 163–201.

4. Kaushik, D., D. Keyes, and B. Smith, "Prospects for CFD on Petaflops Systems," to appear in *CFD Review*, Wiley Press, 1997.

QUENTIN F. STOUT

Electrical Engineering and Computer Science
University of Michigan
Ann Arbor, MI 48109-2122

PROFESSIONAL INTERESTS

My research interests include parallel computing and scientific computing, algorithms and data structures, adaptive statistical designs, and discrete mathematics.

EDUCATION

B.A.	1970	Mathematics, Centre College, Danville, Kentucky
Ph.D.	1977	Mathematics, Indiana University, Bloomington, Indiana

RECENT HONORS AND AWARDS

1999	College of Engineering Team Excellence Award, University of Michigan
1999	Partnership Award, IBM
1995	College of Engineering Service Award, University of Michigan

EMPLOYMENT

1997–Present	Director	Center for Parallel Computing, University of Michigan
1993–1998	Director	Software Systems Research Lab.
1992–Present	Professor	Department of Electrical Eng. and Computer Science University of Michigan

SELECTED PUBLICATIONS

1. R. Miller and Q.F. Stout, *Parallel Algorithms for Regular Architectures: Meshes and Pyramids*, MIT Press, 1996.

2. R. Miller and Q.F. Stout, "Seymour: a portable parallel programming language", *Structured Programming* **11** (1990), pp. 157–171.

3. Q.F. Stout, D.L. DeZeeuw, T.I. Gombosi, C.P.T. Groth, K.G. Powell, "Adaptive blocks: A high performance data structure," *Proc. SC*, 1997.

4. C.R. Clauer, T.I. Gombosi, D.DeZeeuw, A. Ridley, K. Powell, Q.F. Stout, B. Van Leer, T. Holzer, "High performance computer methods applied to predictive space weather simulations," *IEEE Trans. Plasma Science*, 2000, to appear.

5. R. Oehmke and Q.F. Stout, "Parallel adaptive blocks on a sphere", *SIAM Conf. Parallel Proc.*, 2001, to appear.

6. C.P.T. Groth, D.L. DeZeeuw, T.I. Gombosi, H.G. Marshall, K.G. Powell, Q.F. Stout, "Multiscale MHD simulations of a coronal mass ejection and its interactions with the magnetosphere-ionosphere system", submitted.

MAX J. SUAREZ

NASA Seasonal to Interannual Prediction Project
NASA Goddard Space Flight Center
Greenbelt, MD 20771

PROFESSIONAL INTERESTS

Large-scale atmosphere/ocean interactions, climate modeling, numerical methods, parameterization of subgrid-scale processes in atmospheric models, maintenance of the atmospheric general circulation, climate sensitivity.

EDUCATION

B.S.	1971	Engineering Science, University of Florida
M.E.	1972	Engineering Science University of Florida
M.A.	1974	Geophysical Fluid Dynamics, Princeton University
Ph.D.	1976	Geophysical Fluid Dynamics, Princeton University

EMPLOYMENT

1983–Present	Meteorologist	NASA/Goddard Space Flight Center
1976–1983	Assistant Professor	UCLA

SELECTED PUBLICATIONS

1. Moorthi, S., and M. J. Suarez, 1992: Relaxed Arakawa-Schubert: A Parameterization of Moist Convection for General Circulation Model. *Mon. Wea. Rev.*, **120**, 978-1002.

2. Koster, R. D., and M. J. Suarez, 1992: A Comparative Analysis of Two Land Surface Heterogeneity Representations. *J. Climate*, **5**, 1379-1390.

3. Suarez, M. J., and D. G. Duffy, 1992: Terrestrial Superrotation: A Bifurcation of the General Circulation. *J. Atmos. Sci..*, **49**, 1541-1554.

4. Held, I. M., and M. J. Suarez, 1994: A Proposal for the Intercomparison of Dynamical Cores of Atmospheric General Circulation Models. *Bull. Amer. Meteor. Soc.*, **75**, 1825-1830.

5. Schaffer, D. S., and M.J. Suarez, 2000: Next Stop: Teraflop; The Parallelization of an Atmospheric General Circualtion Model. *High Performance Computing*, **submitted.**

6. Mehta, V., and M. J. Suarez, 2000: Decadal-multidecadal Variations of ENSO: 1909-1988. *J. Geophys. Res. Letters*, **27**, 121-124.

7. Mehta, V., M. J. Suarez, J. Manganello, and T. L. Delworth, 2000: Oceanic Influence on the North Atlantic Oscillation and Associated Northern Hemishphere Climate Variations: 1959-1993. *J. Geophys. Res. Letters*, **27**, 121-124.