High Resolution coupled land-atmosphere system using Land Information System and Weather Research and Forecasting model enabled by ESMF

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Abstract

The accurate characterization of the complex dynamics of land-atmosphere interactions is important for improving our understanding of the hydrological cycle, interannual climate variations as well as the mean climate. The surface water and energy fluxes, which represent the interaction between the land and atmosphere, are strongly dependent on the land surface characteristics. As a result, the realistic representation of the land surface boundary plays a critical role in land-atmosphere simulations. NASA's Land Information System (LIS) is a high resolution land data assimilation system that integrates the use of high resolution satellite and other observational data, advanced land surface models, data assimilation techniques, and high performance computing tools. The Earth System Modeling Framework (ESMF) is a collection of software tools to foster interoperability, portability and code reuse in Earth Science applications. ESMF provides a number of utilities that can be customized to enable interaction between different Earth system models. LIS is coupled to the Weather Research and Forecasting (WRF) model using ESMF technologies to provide high resolution land surface initial and boundary conditions in a coupled simulation. Employing LIS as the land modeling component in the coupled system enables the use of an ensemble of land surface models, high resolution data, and data assimilation techniques. The coupled system is benchmarked on a high performance computing environment to ensure scalable performance.

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1. Introduction

The dependence and the sensitivity of the climate system to the land surface boundary have been reported in many studies (e.g. Walker and Rowntree (1977); Shukla and Mintz (1982); Marguilis and Entekhabi (2004)). In recent years, considerable amount of effort has been devoted to developing realistic representation of land surface boundary in coupled simulations. NASA's Goddard Space Flight Center has developed a Land Information System (LIS; Peters-Lidard et al. (2004)) capable of simulating global land surface conditions at spatial resolutions down to 1km. LIS is a high performance Land Data Assimilation System that consists of several land surface models run offline using observationally-based precipitation, radiation, and meteorological inputs, and surface parameters. LIS provides the capability to integrate land surface simulation, observation, and analysis methods to accurately determine land surface energy and water states. The design of LIS is based on object oriented principles, with subcomponents such as the land surface models, data assimilation algorithms, high performance computing tools, specified using adaptable interfaces to enable rapid prototyping and development of new capabilities. The ability of LIS to operate at the same fine spatial scales of the atmospheric boundary layer and cloud models helps to improve water and energy cycle modeling and prediction capabilities.

A typical coupled land-atmosphere model consists of components for land surface and the atmosphere, which interact through exchanges of data. Although many coupled systems exist at different research institutions, the increasing complexity of these models and the lack of uniform interface standards for coupling have impeded the use of these models across organizations. The Earth System Modeling Framework (Hill et al. (2004)) is a project intended to develop standards-based, open-source software tools to enable software reuse, interoperability and performance portability in Earth Science Applications. The ESMF software primarily consists of a superstructure for coupling and exchanging data between components (e.g., atmosphere, land) and an infrastructure consisting of tools and utilities to speed up construction of components and to ensure consistent, guaranteed component behavior.

In this article, we describe the coupled system to conduct high resolution land-atmosphere simulations using LIS and the Weather Research and Forecasting model (WRF; Michalakes et al. (2001)) enabled by the use of ESMF. In the sections that follow, we describe the architecture of the coupled system and the parallel performance benchmarks on a high performance computing environment.

2. Description of the ESMF-enabled Land-Atmosphere coupled system

The coupled system enabled by ESMF follows a sandwiched architecture, where the user-code components fit between the ESMF superstructure and the ESMF infrastructure as shown in Figure 1. The ESMF superstructure provides methods for data exchange between components. The ESMF Infrastructure provides integrated tools for time management, profiling, intra-component communication, and structural representations of grids and fields, among many standard modeling functions. The user defined components can be different models themselves or tasks within a model component.

A model component using ESMF is organized to perform three major functions: initialization, run, and finalization. The initialization methods typically implement the initialization of parameters, initial and boundary conditions, and any other model setup. The run method provides the model simulation methods and the finalization routine provides methods to properly shut down the model operations. The ESMF superstructure maps these routines defined for each model component to the standard interfaces that the main program calls during execution using a mechanism called *setServices*. The user-defined model components use special objects called *ESMF_State* for inter-component data exchanges. Every component accepts one or more *ESMF_State*s as import states and produces one or more *ESMF_State*s as export states.

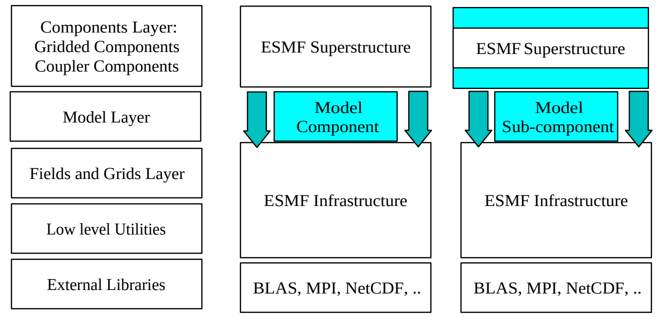

Figure 1: Structure of a coupled ESMF application

The WRF software follows a modular structure with complex functionalities encapsulated into a three main hierarchical levels. The highest level corresponds to the driver layer and the lowest level corresponds to the model layer. The mediation layer provides the interface between the driver and the model layers. The driver performs the top-level initializations, time-stepping, I/O, instantiating domains, setting up domain decomposition, processor topologies, and other aspects of parallelism. The interaction between LIS and WRF is established at the surface driver model layer in WRF, with the coupling to LIS implemented as a model subcomponent of WRF.

The sequence of component interactions follow the structure shown in Figure 2. There are two main model components: *lisComp* representing LIS, and WRF. The ESMF superstructure structures required to enable coupling on the WRF side, is implemented in the WRF driver layer. *lis2wrfCpl* and *wrf2lisCpl* represent the coupler components that perform data exchanges between LIS and WRF. The import and export states from WRF and

LIS are named *wrfImport*, *wrfExport*,*lisImport*, and *lisExport*, respectively. During the simulation, the surface driver in WRF invokes the WRF to LIS coupler, which transforms the *wrfExport* to *lisImport*. Subsequently, *lisComp* is executed followed by the transformation of *lisExport* to *wrfImport* by the *lis2wrfCpl* coupler. This process is repeated during every invocation of the surface driver. The WRF and LIS components are run on predefined layouts for each component, and the couplers are run on the global superset of the processors.

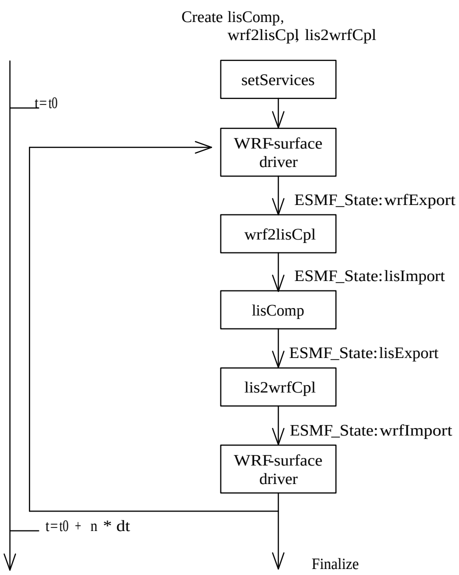

Figure 2: Sequence of component interactions for the LIS-WRF coupling using ESMF

A number of land surface models from a number of different organizations have been implemented in LIS including the Noah land surface model from National Center for Environmental Prediction (NCEP), Community Land Model (CLM) developed at National Center for Atmospheric Research (NCAR), Variable Infiltration Capacity (VIC) model from University of Washington and Princeton University, Mosaic and HySSIB models developed at NASA Goddard Space Flight Center, among others. The ESMF structures implemented in LIS required for coupling are independent of any particular land surface model. Each land surface model in LIS implements the abstract interfaces for defining the land surface model specific import and export states. A land surface model in LIS can be used for coupled simulation with WRF once these interfaces are implemented, without having to adapt each land surface model separately to be ESMF-compliant. Currently two land surface models in LIS (Noah and CLM) have been extended to work in a coupled simulation.

3. Analysis of computational performance

One of the primary design goals of ESMF is to enable performance portability and efficient operation of model components when coupled using ESMF. In this section, we present some performance benchmarks for the coupled system. All simulations were conducted on the HP/Compaq SC45-halem system at the NASA Goddard Space Flight Center, using Noah as the land surface model in the coupled system.

The LIS-WRF system was run on both 100x100 and 200x200 domains at 1km, varying the number of processors. The use of multiprocessors provides significant computational savings compared to the execution on a single processor. Comparison of the speedup obtained on the multiprocessor environment for the two systems is compared on Figure 3. To assess the overhead of the ESMF structures, the computational performance of the ESMF-based coupled system was compared with that of the equivalent, non-ESMF based system. Comparisons shown in Figures 4 indicate that the overhead of the ESMF is minimal. The simulations used in this article employed identical model grids across different components. As a result, the computational overhead for the transformation of gridded, exchanged data is not accounted for in these results.

4. Summary

NASA's Land Information System has been successfully coupled with the Weather Research and Forecasting model using ESMF technologies. The results presented in this article suggest that the computational overhead due to ESMF compliant coupling is minimal. How-

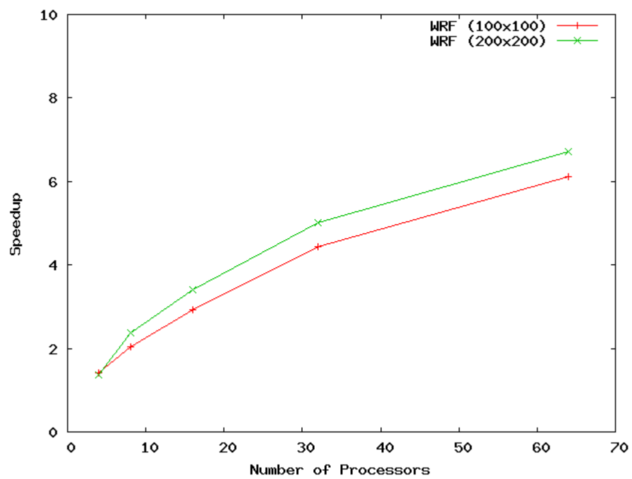

Figure 3: Speedup vs the number of processors for the ESMF-based coupled system

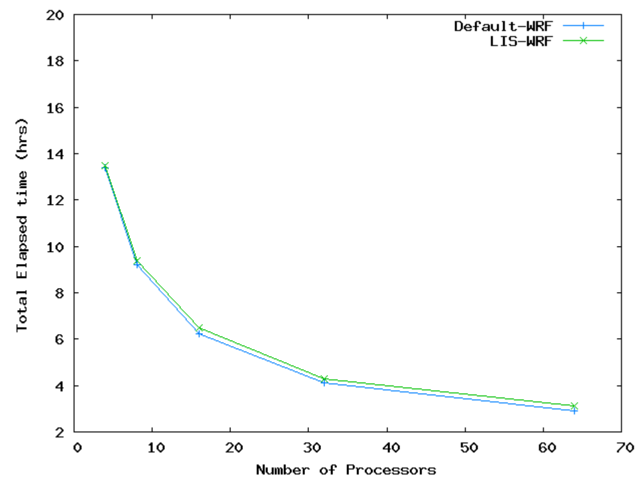

Figure 4: Comparison of the computational performance of the ESMF-based coupled system with the default, non-ESMF system

ever, we do not currently support executing land and atmosphere components on different model grids. This ESMF-enabled capability will be adopted in the future.

The use of LIS as the land modeling component enables not only the use of all the land surface models in LIS, but also the use of high resolution data access and distribution, high peformance computing, and data assimilation tools implemented in LIS. The interaction of LIS and WRF through ESMF will enable studies to investigate the nature of interaction and feedback between land and the atmosphere using different modeling tools in LIS and WRF.

5. Acknowledgments

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