Coupling High Resolution Earth System Models Using Advanced Computational Technologies

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Abstract— The NASA/GSFC Land Information System (LIS) has now been successfully coupled to the Weather Research and Forecasting (WRF) and Goddard Cumulus Ensemble (GCE) models using parallel techniques in a manner compliant with the Earth System Modeling Framework (ESMF). LIS is a high-performance Land Data Assimilation System (LDAS), developed under funding from ESTO-CT's Round-3 CAN, whose TRL3 technologies have been advanced to TRL4 the current ESTO-AIST project. The original LIS consists of several land surface models run in an uncoupled manner (i.e. "offline") using observationally-based precipitation, radiation and meteorological inputs, and surface parameters including Moderate Resolution Imaging Spectroradiometer (MODIS)-based Leaf Area Index (LAI). In this project, LIS is first executed in an uncoupled manner in order to provide soil moisture and soil temperature initial conditions for a case study period (the 2002 International H2O Project (IHOP) field program). Then, during the case study period, the land surface (LIS) and atmospheric (WRF/GCE) models are executed in a coupled manner using ESMF. The simulations using realistic initial land surface states from LIS showed significant improvements in simulating land-atmosphere interactions.

I. INTRODUCTION

The dependence and the sensitivity of the climate system to the land surface boundary have been reported in many studies (e.g. [10], [7], [3]). In recent years, considerable amount of effort has been devoted to developing realistic representation of land surface boundary in coupled simulations. NASA's God-dard Space Flight Center has developed a Land Information System (LIS [5], [2], [9]) capable of simulating global land surface conditions at spatial resolutions down to 1km. LIS is a high performance Land Data Assimilation System (LDAS [6]) 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 1km modeling capability enables LIS to directly ingest the vast array of Earth Observing System (EOS)-era observations such as those available from Terra and Aqua. 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 [1]. 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, enabled by the use of ESMF. LIS is coupled to the Weather Research and Forecasting (WRF [4]) and the Goddard Cumulus Ensemble (GCE [8]) models. In the sections that follow, we describe the architecture of the coupled system, the parallel performance benchmarks on a high performance computing environment, and the impact of LIS on coupled land-atmosphere simulations.

II. DESCRIPTION OF THE ESMF-ENABLED LAND-ATMOSPHERE COUPLED SYSTEMS

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.
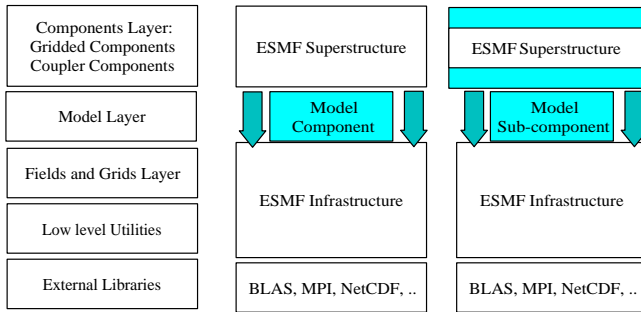

Fig. 1.   Structure of a coupled ESMF application

A model component using the ESMF model 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. 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.

The coupling sequence between GCE and LIS is shown in Figure 2. There are two main model components; *lisComp*, and

gceComp, representing LIS and GCE, respectively. *lis2gceCpl* and *gce2lisCpl* represent the coupler components that perform the data exchange between the model components. The import and export states from GCE and LIS are named *gceImport*, *gceExport, lisImport, and lisExport*, respectively. The simulation starts at *t=t0* and cycles *n* times. At the beginning of the simulation, both model components and coupler components are created. The model components are instantiated on their respective model grids and processor layouts. The coupler components are instantiated on the global superset of the processors used. The *setServices* utility is used to register the components of the model and the coupler components to be invoked by the main program. The *gceComp* provides an export state (*gceExport*) to the coupler from atmosphere to land (*gce2lisCpl*). *gce2lisCpl* uses *gceExport*, transforms it into *lisImport* and provides it to the *lisComp* component. Similarly, the *lisExport* state from the *lisComp* is transformed to *gceImport* state by the land to atmosphere (*lis2gceCpl*) coupler. The process continues for *n* cycles.
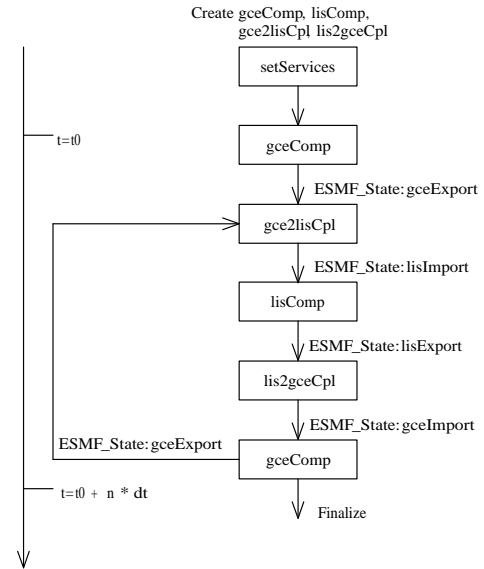
Fig. 2.   Sequence of component interactions for the LIS-GCE coupling using ESMF

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 coupling between LIS and WRF is established at the surface driver model layer in WRF. In contrast to the LIS-GCE coupling, where the interfaces between LIS and GCE are established outside the models themselves, the interaction with LIS in WRF is established as a model subcomponent.

The sequence of component interactions follow the structure shown in Figure 3. Though no explicit WRF model com-

ponent is created, an equivalent ESMF notion of the grid and the processor layout used by WRF is implemented in the WRF driver layer. During the simulation, the surface driver in WRF invokes the WRF to LIS coupler (*wrf2lisCpl*), which transforms the export state from WRF (*wrfExport*) to *lisImport*. Subsequently, *lisComp* is executed followed by the transformation of *lisExport* to the WRF import state, (*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.

Fig. 3. Sequence of component interactions for the LIS-WRF coupling using ESMF

III. 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 both coupled systems. All simulations were conducted on the HP/Compaq SC45-halem system at the NASA Goddard Space Flight Center.

The LIS-GCE coupled system was run on both 128x128 and 256x256 domains at 1km, and 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 4. To assess the overhead of the ESMF structures, the computational performance of the ESMF-based coupled systems were compared with that of the equivalent, non-ESMF based systems. Comparisons shown in Figures 5 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.

Fig. 4. Speedup vs the number of processors for the ESMF-based coupled systems

IV. Impact of LIS-generated land surface states in coupled simulations

In order to evaluate the impact of using realistic land surface initial conditions in coupled simulations, a case day of June 12th, 2002 was chosen, which was expected to highlight the impact of initial soil thermodynamic profiles and the mesoscale circulation associated with the land surface forcing. This day also had fairly light winds at the surface and large scale synoptic forcing was fairly weak. Convection was observed beginning in the late afternoon near the center of our chosen domain.

The modeling domain consisted of 256x256 horizontal grid points, with a 1km grid spacing, and 41 vertical levels extending to 100mb. The atmospheric initial and boundary conditions were set using the WRF Standard Initialization (WRFSI) software. We performed 3 different integrations that had the soil moisture and temperature profiles initialized by WRFSI, a 10 year spinup using the Global Data Assimilation System (GDAS) forcing from NOAA, and a 10 year spinup using North American Land Data Assimilation System (NLDAS) forcing, which uses the Stage II radar and gauge precipitation data. The GDAS forcing has a resolution of 2.5 degrees, while the NLDAS has a 1/8th degree resolution. All integrations were otherwise identical and each were ran for 24 hours, starting at 12GMT on June 12th, 2002.

A spatial analysis of the integrations showed that the WRFSI soil initialized integration produced no features resembling those observed on the actual day. The precipitation produced was minimal and no mesoscale convective clusters developed. The precipitation that did occur was nearly five hours after the actual system had propagated the domain. In the integration using the land surface states produced by LIS from the GDAS spinup, a system developed that was similar to the case day, but the precipitation development occurred several hours later.
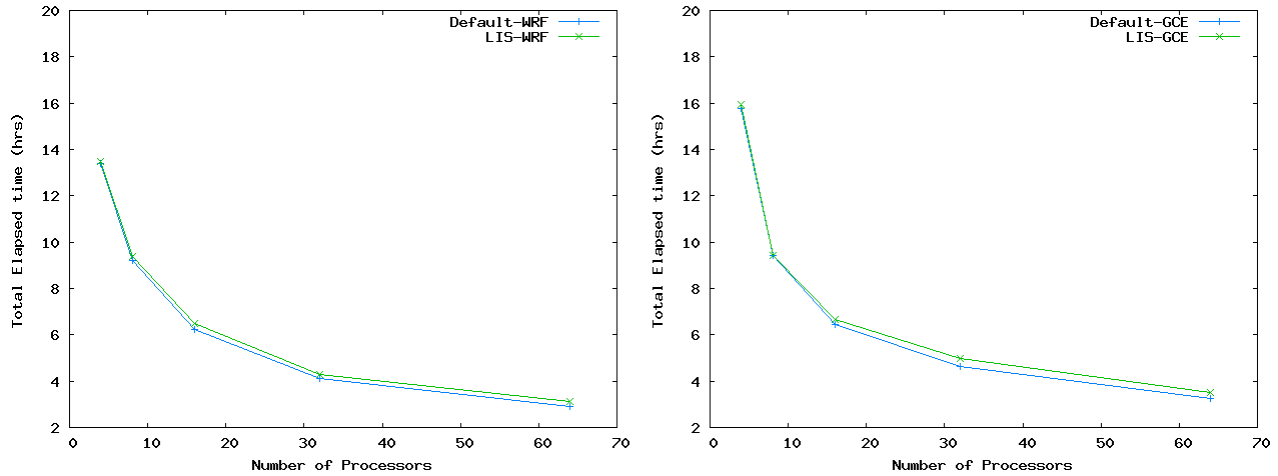
Fig. 5. Comparison of the computational performance of the ESMF-based coupled systems with the default, non-ESMF systems

Figure 6 shows a comparison of the 24 hour accumulated precipitation using the default soil initialization in WRF and the simulation using the spunup fields from LIS. Both these results are compared with the observed radar derived precipitation. The simulation using initial conditions from LIS provides a more realistic representation of the observed precipitation.

The land surface states produced from the NLDAS spinup uses a higher resolution forcing and observed precipitation data. As a result, the simulation using the NLDAS spinup conditions further improved the predictions shown in Figure 6, showing better agreement with the observations both temporally and spatially. Shown in Figure 7 is the domain averaged precipitation versus time for the 24 hour integrations. Also shown on the Figure is the radar derived, bias corrected Stage II NCEP precipitation data. The Figure indicates that the WRFSI soil initialized integration did not capture the magnitude or the temporal characteristics of the day. There is substantial improvement when the LIS-GDAS spinup fields are used for the initial profiles. Finally, the best agreement in terms of magnitude and temporal evolution was achieved using the NLDAS forced spinup fields to initial the soil conditions.

Fig. 7. Comparison of the domain integrated precipitation using different coupled system simulations

V. SUMMARY

NASA's Land Information System has been successfully coupled with the Weather Research and Forecasting and Goddard Cumulus Ensemble models, in a manner fully compliant with ESMF. The results presented in this article suggest that the computational overhead due to ESMF compliant coupling is minimal. However, 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 land surface initial conditions for the coupled simulations were generated by running LIS "uncoupled" (i.e., using observed/model-derived meteorological inputs) for 10 years. This is necessary because deep soil moistures and temperatures require long integrations to reach dynamic equilibrium. Our case study results sugg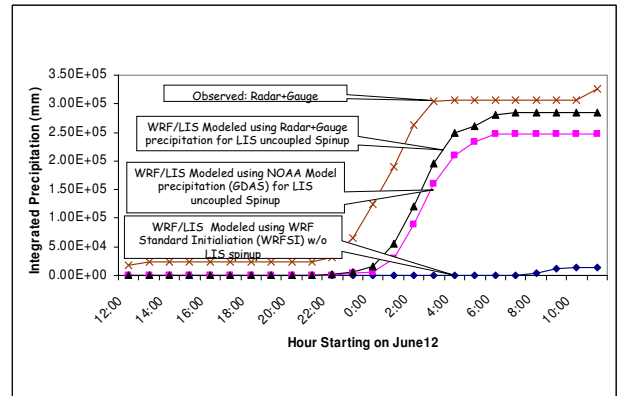est that the soil thermodynamic profiles generated from LIS significantly improved the coupled system estimates relative to the standard initialization.

The ongoing work will focus on simulating different case days during the IHOP period, including an investigation of the impacts of initial and boundary conditions on the simulations. For example, we will investigate the impact of different land surface models (e.g., the Community Land Model (CLM)) and the impact of spatial extent and resolution. So far this project has advanced model coupling technologies from TRL3 to TRL4. After completion of the IHOP case studies with the LIS-GCE system, we will further advance to TRL5, with the goal of advancing to TRL6 by the completion of the project.

24 hour accumulated precipitation with default soil initialization

24 hour accumulated precipitation with LIS 10 year spinup soil initialization

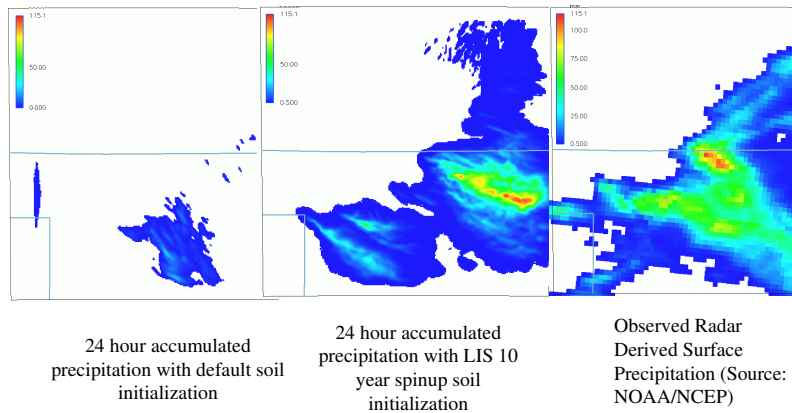Observed Radar Derived Surface Precipitation (Source: NOAA/NCEP)

Fig. 6. Comparison of the 24 hour accumulated precipitation with the default WRF initialization and with using the LIS spunup land surface states with the observed radar derived precipitation from NOAA/NCEP

VI. ACKNOWLEDGMENTS

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