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Coupling climate and hydrological models: Interoperability through Web Services

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ABSTRACT

Understanding regional-scale water resource systems requires understanding coupled hydrologic and climate interactions. The traditional approach in the hydrologic sciences and engineering fields has been to either treat the atmosphere as a forcing condition on the hydrologic model, or to adopt a specific hydrologic model design in order to be interoperable with a climate model. We propose here a different approach that follows a service-oriented architecture and uses standard interfaces and tools: the Earth System Modeling Framework (ESMF) from the weather and climate community and the Open Modeling Interface (OpenMI) from the hydrologic community. A novel technical challenge of this work is that the climate model runs on a high performance computer and the hydrologic model runs on a personal computer. In order to complete a two-way coupling, issues with security and job scheduling had to be overcome. The resulting application demonstrates interoperability across disciplinary boundaries and has the potential to address emerging questions about climate impacts on local water resource systems. The approach also has the potential to be adapted for other climate impacts applications that involve different communities, multiple frameworks, and models running on different computing platforms. We present along with the results of our coupled modeling system a scaling analysis that indicates how the system will behave as geographic extents and model resolutions are changed to address regional-scale water resources management problems.

Software availability

The code for this system and instructions to reproduce our results is available at: http://esmfcontrib.cvs.sourceforge.net/viewvc/esmfcontrib/HydroInterop/.

1. Introduction

Projections of the Earth's climate by models provide the primary information for anticipating climate-change impacts and evaluating policy decisions. Changes in the water cycle are expected to have impacts on, for example, public health, agriculture, energy generation, and ecosystem services (Parry et al., 2007). The integration of information from climate-model projections with the tools used by practitioners of water management is a core interest of those developing strategies for adaptation to climate change (Raucher, 2011). Often a hydrological model that is formally separated from a climate model is used in these applications (Graham et al., 2007). In this paradigm, climate projections may be used as a forcing function to drive the decoupled hydrologic simulation model. These applications assume there is no significant feedback from the land surface to the climate system (either regional or global), and while this assumption may be true for small

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watersheds, as hydrologists continue to scale their models up to river basin and regional systems, this assumption of no feedback loop will need to be addressed. Therefore both intuitively and theoretically, we expect hydrological models to perform better when they are coupled in some way to a global or regional climate model (Xinmin et al., 2002; Yong et al., 2009).

A second paradigm for the coupling of hydrological models into global climate systems is to allow two-way communication, so that simulating feedback loops is possible. There are scientific and software challenges posed by either form of coupling. The difference in spatial scales provide an intrinsic challenge when coupling climate and watershed-scale hydrologic models. For a hydrological model used in agricultural decision-making, intrinsic scales must adequately represent the drainage of the streams, the specifics of the land and vegetation in the watershed, surface topography at accuracies of less than a meter, and the surface type of the built environment. Even with the highest resolution climate models likely to be viable in the next five years which promise grid cells on the order of 100 km^2, there are differences of several orders of magnitude in the spatial scales. Transference of information in a physically meaningful way across these scales, large-to-small and small-to-large, is neither scientifically nor algorithmically established.

The work described here is forward looking in that we explore loose coupling of a climate model and a hydrological model with two-way communication between the models using Web Services. This type of coupling might be viewed as a first step toward linking climate models to real-world applications. With the full realization that, from an Earth-science perspective, the spatial resolution of the climate model might not justify the coupling at this time, we propose that there are scientific and algorithmic challenges that are worth addressing. Rather than waiting until the climate models are at some undefined state of readiness to start the coupling, then begin to develop the coupling strategies, we are co-developing the coupling with the models. This will help both to define the scientific foundation of the coupling and to evolve the algorithms in concert with the scientific investigation. This work is related to activities in the computational steering community (e.g., Parker et al., 1998; Malakar et al., 2011) in that we use Web Services to pass data between desktop and climate and weather models. As we move past exploratory and prototyping work, we believe that work related with this field will help to define both the scientific foundation of the coupling and evolve the algorithms in concert with the scientific investigation.

The work advances on existing work in Earth System Modeling Framework (ESMF) and standards by exploring how two existing modeling frameworks, ESMF and the OpenMI Configuration Editor (OmiEd), can be integrated for cross-framework simulations. By leveraging a service-oriented architecture, we show that a climate model implemented within ESMF can be made available as a Web Service, and that an OpenMI-based client-side component can then wrap the ESMF service and use it within an OmiEd configuration. We selected OmiEd (which adopts the OpenMI standard) as the client application in our work because of past work to create ESMF services that could be brought into OmiEd. This work builds on the proposed concept of modeling water resource systems using service-oriented architectures (Laniak et al., 2013; Goodall et al., 2011; Granell et al., 2010) and extends the work to leverage ESMF models in a personal computer-based integrated model configuration. It extends on this work by specifically exploring coupling across modeling frameworks, in particular modeling frameworks that target different communities (climate science and hydrologic science) that have different models, best practices, and histories for building computer-based model simulation software. By using a service-oriented, loose-coupling approach, we are able to maintain state-of-the-art community supported models within the integrated modeling system.

There are other aspects of this work that address the use of climate projections in decision making. As discussed by Lemos and Rood (2010) and others, there are many research questions to be answered in bridging scientists' perceptions of the usefulness of climate information and practitioners' perceptions of usability. Co-generation of knowledge and methodology has been shown to be an effective way to address these questions; discipline scientists, software specialists, and practitioners learn the constraints that each must face. This improves the likelihood of successful use of climate information. In the development that we are pursuing, we will be using a hydrological model that is widely used in agricultural decision-making. Thus, we are not only coupling Earth science models implemented for different spatial scales, but we are laying the foundation for diverse communities of experts to interact in a way they have not done previously by enabling bidirectional coupling of distributed models outside the scope of a single integrated climate model.

Given this motivation, the first objective of our research was to design a system capable of coupling widely used models in the atmospheric and hydrologic communities in a way that maintains the original structure and purpose of each model but provides coupling of flux and state variables between the two models. The second objective was to assess the applicability of the approach by conducting a scaling analysis experiment. The purpose of the scaling analysis was to quantify the performance of the coupled hydro/climate model in terms of the hydrology model execution time, the climate model execution time, and time required for transferring data between the two models. We present the methodology for addressing these two study objectives in the following section. We then present the results of the scaling analysis, and discuss our findings for the applicability of our proposed approach for model coupling.

2. Methodology

Our methodology consists of two main tasks. First, we designed an overall system to consist of three components: a hydrological model, an atmospheric climate model, and the driver application. The design of this system, which we refer to as the Hydro-Climate Modeling System, is described in the first subsection and a prototype implementation of the system is described in the second subsection. Second, we devised a series of experiments with the goal of estimating how the Hydro-Climate Modeling System would scale as the size of the study region increases. These experiments are meant to provide an approximate measure of scaling that will aid in optimizing performance of the system and improve understanding of the applicability of the approach for simulating regional-scale hydrologic systems. Details of the scaling analysis design are presented in the third and final subsection of this methodology section.

2.1. Hydro-Climate Modeling System design

Within this general service-oriented framework, the target of our prototype is a two-way coupled configuration of the Community Atmosphere Model (CAM) and the hydrological model Soil and Water Assessment Tool (SWAT) that captures the coupled nature of the physical system. The intent of our coupling was not to produce realistic simulations, but to explore the behavior of a technical solution spanning high performance computing and Web Services. Thus the specifics of the configuration matter here only insofar as they represent a scientifically plausible exchange, and serve as a starting point for design decisions and for exploring the behavior and scaling of the coupled system. We fully expect that the models used, and the specifics of the coupling, may change as our investigation continues and new models and resources become available. The use of models with structured component interfaces facilitates such exploration because of the "plug-and-play" functionality provided through component interface standardization.

In the chosen configuration, CAM supplies to SWAT a set of five fields (surface air temperature, wind speed, precipitation, relative humidity, and solar radiation) for each 30 min interval of the model simulation. SWAT passes one field, evaporation, back to CAM also on a 30 min interval. CAM was run in a Community Earth System Model (CESM) configuration that included active atmosphere, land, and ice model components, as well as a data ocean representation (in place of an active ocean