Abstract. CSDMS, The Community Surface Dynamics Modeling System, is an NSF funded project whose focus is to aid a diverse community of earth and ocean system model users and developers to use and create robust software quickly. To this end, CSDMS develops, integrates, archives and disseminates earth-system models and tools to an international (67 country) community with the goal of building the set of tools necessary to model the earth system. Modelers use CSDMS for access to hundreds of open source surface-dynamics models and tools, as well as model metadata. Such a model repository increases model transparency and helps eliminate duplication by presenting the current state of modeling efforts. To increase software sustainability, composability and interoperability, CSDMS promotes standards that define common modeling interfaces, semantic mediation between models, and model metadata. Through online resources and workshops, CSDMS promotes software engineering best practices, which are unfamiliar to many developers within our modeling community. For example, version control, unit testing, continuous integration, test-driven development, and well-written clean code are all topics of the educational mission of CSDMS.

1. The Community Surface Dynamics Modeling System

The mission of the Community Surface Dynamics Modeling System (CSDMS) is to help a diverse modeling community toward common goals and standards. This effort involves creating:

- a repository of source code and metadata for open-source models and tools (Section 2)
- reusable plug-and-play model components and a framework within which they can be coupled to create new models (Section 3)
- an efficient and open modeling community through standards (Section 3.1) and education (Section 4)

In building a modeling framework, CSDMS has leveraged several existing, well-established and open-source software tools. For example, CSDMS uses tools from the Common Component Architecture (CCA) toolchain: Babel and Bocca. Babel provides interoperability between components written in different languages; it currently supports C, C++, Fortran, Java, and

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Python. Bocca helps with creating CCA-compliant components and managing CCA component projects.

CSDMS has developed innovative model/component interfaces that promote model reuse and interoperability, including the Basic Model Interface (BMI - Section 3.1.1), which uses the CSDMS Standard Names (Section 3.1.2) and a framework within which models can be coupled and enhanced with a set of BMI-compatible service components. The CSDMS Web Modeling Tool (WMT - Section 3.2) is a web-based application that provides a graphical interface to this framework and allows users to compose new models by connecting and configuring components in a simple, browser-based graphical interface.

2. Organizing and Documenting Open-Source Models

2.1. The CSDMS Model Repository. Open-source software reduces redundancy, provides transparency through external review and makes research replicable, which is fundamental to scientific practices [6]. Software accessibility is a key value of the CSDMS mission. CSDMS ensures code developed by individual researchers or small research teams remains accessible beyond the lifetime of a specific research project. Code developers are required to distribute their codes under open-source licenses.

CSDMS has built an online model repository that not only contains model source code but also documents the submitted code as model metadata, runs basic smoke-tests of the models, (optionally) maintains the source code in a CSDMS-hosted version control system, and provides easy downloads of the original source. The repository now contains over 200 models and tools (over 4M lines of code) and has received over 13k model downloads.

2.2. Digital Object Identifiers for Numerical Models. CSDMS has implemented a Digital Object Identifier (DOI) system for software within its model repository to guarantee recognition to software contributors. CSDMS was among the first software venues to assign DOIs to open source software. The advantages of adopting a DOI system for open source software are:

- Guarantee credit to the software developer
- Easily reuse and replicate research as software is directly locatable
- Increase software visibility: DOI content is 5 times more likely to deliver active links than content without.
- Provide funding agencies with the ability to track usage, to measure impact.

Only stable versions of open source software that are physically hosted through the CSDMS repository will be assigned a DOI. For model software citations, CSDMS recommends the following the DataCite guidelines [2].

Developer, A., Developer, B. (Year of publication). Name of the model, Model Version. Identifier.
3. Reusable Components

3.1. Sustainability and Interoperability Through Standards.

3.1.1. The Basic Modeling Interface. The Basic Modeling Interface\(^\ast\) (BMI) is a component-coupling library interface specification designed by CSDMS \[^8\,^9\]. In this context, a component is software that models a particular environmental process and can be plugged into another component.

The BMI specification was designed without any particular model-coupling framework in mind. Rather, it was designed to be framework agnostic. We recognize model-coupling frameworks and tools may come and go but the functionality a framework requires from its components will be significantly more long-lived. Thus, a component should outlive any framework that it might operate within.

The BMI identifies the entry points into software components that provide a calling application with the necessary level of control to connect components. CSDMS, as well as other modeling frameworks such as ESMF \[^5\], OpenMI \[^4\], and OMS \[^3\], identifies an interface that, at a minimum, provides functionality to initialize, update, and finalize a component. For more complicated (and 2-way) coupling, components must implement BMI methods providing data access, and model metadata. For data access, BMI defines a set of getter and setter methods that allow model components to present internal data for both reading and writing.

CSDMS has found that BMI is an acceptable target for model developers. The use of BMI has also dramatically reduced the effort required by CSDMS staff to create and maintain components. So long as a model component strictly exposes a BMI, it can automatically be incorporated into the CSDMS model-coupling framework where it can then connect to compatible components to form larger models and obtain additional functionality through BMI compatible tools (for example, NetCDF output, grid mapping).

3.1.2. CSDMS Standard Names. The CSDMS Standard Names\(^\dagger\) are a common language for variable names exchanged between models. They play an important role in the BMI as they provide a mapping of a model’s internal variable names to a common language used by the BMI getter and setter functions.

Most models require input variables and produce output variables. For model components to be reusable and interoperable (either within the CSDMS framework or any framework in general) a set of components become a complete model when every component is able to obtain the input variables it needs from another component. The CSDMS Standard Names were developed to provide a practical solution to this semantic mediation problem \[^8\,^9\]. The CSDMS Standard Names provide a comprehensive set of

\(^\ast\)https://github.com/csdms/bmi
\(^\dagger\)https://github.com/csdms/standard_names
naming rules and patterns for creating unique labels for model variables that are not specific to any particular modeling domain.

3.2. Connecting and Running Models Through the Web. The CSDMS Web Modeling Tool\textsuperscript{\ref{fig:1}} (WMT) is a web application that provides an Ajax client-side (the WMT client\textsuperscript{\ref{fig:1}}) graphical interface (Figure \ref{fig:1}) and a RESTful server-side database and API (the WMT server\textsuperscript{\ref{fig:1}}) that allows users to build and run coupled Earth system models on a high-performance computing cluster from a web browser. WMT was designed with four objectives:

- \textit{Accessibility}. As a web-based application, if you have access to the Internet, you have access to WMT.
- \textit{Integration}. Easily hyperlink from WMT to resources on the CSDMS modeling portal (model documentation, labs, lectures, tutorials)
- \textit{Portability}. WMT has a native JavaScript interface, so it can be accessed on any modern web browser
- \textit{Maintenance}. Because modern browsers tend to adhere to web standards, which lead to fewer cross-compatibility issues than operating systems, only one version of WMT needs to be developed and maintained.

With WMT, users can: \textit{run} single component models, build (2-way) \textit{coupled models}, view and \textit{edit} model parameters, and \textit{share} saved models with others in the community.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{The CSDMS Web Modeling Tool}
\end{figure}

\begin{itemize}
\item \textsuperscript{\ref{fig:1}}https://csdms.colorado.edu/wmt
\item \textsuperscript{\ref{fig:1}}https://github.com/csdms/wmt-client
\item \textsuperscript{\ref{fig:1}}https://github.com/csdms/wmt
4. Education and Evaluation of CSDMS Tools

CSDMS constantly evaluates the effectiveness of its tools and standards through user feedback from clinics and tutorials and one-on-one interviews with CSDMS members. Modeling courses at the University of Colorado, clinics at the International Summer Institute at the University of Minnesota, and clinics at CSDMS Annual Meetings are the dominant forums for this testing and feedback.

Over the last 4 years over 150 graduate students - from geography, hydrology, geology, oceanography, earth sciences and engineering departments - have enrolled in intensive CSDMS-run modeling courses. These courses provide an excellent use case for us to test usability and access to our tools. Students reported in post-course surveys that they were unfamiliar with the use of models on a high performance computing cluster beforehand (rated their familiarity as 1.5 average on a Likert scale of 1-5), but ended the courses with familiarity and being more comfortable with running and changing simulations as well as visualizing results (average rating approaches 4) [7].

Course and clinic materials are posted online as educational resources. CSDMS develops WMT-specific help pages for all models currently available as components, so that users can easily learn about model parameters and input files. In addition, we are developing web-based video tutorials that show how to run models.

5. Summary: Building an active and efficient modeling community

CSDMS provides cyber-infrastructure to promote the quantitative modeling of earth surface processes. The US National Science Foundation funds CSDMS, but the community is international and includes industry and federal agency representatives in addition to members from academic institutions. The initiative has been growing with more than 150 people per year. CSDMS now fosters a community of approximately 1200 scientists who work on prediction of the movement of fluids, and the production, erosion, transport, and deposition of sediment and nutrients in landscapes and seascapes.

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References

[1] Rob Armstrong, Dennis Gannon, Al Geist, Katarzyna Keahey, Scott Kohn, Lois McInnes, Steve Parker, and Brent Smolinski. Toward a common component architecture for high-performance scientific computing. In High Performance Distributed Computing, 1999. Proceedings. The Eighth International Symposium on, pages 115–124. IEEE, 1999.
[2] Jan Brase. Datacite—a global registration agency for research data. In *Cooperation and Promotion of Information Resources in Science and Technology, 2009. COINFO’09. Fourth International Conference on*, pages 257–261. IEEE, 2009.

[3] Olaf David, Steven L Markstrom, Kenneth W Rojas, Lajpat R Ahuja, and Ian W Schneider. The object modeling system. *Agricultural system models in field research and technology transfer*, pages 317–331, 2002.

[4] J Gregersen, P Gijsbers, and S Westen. Openmi: Open modelling interface. *Journal of Hydroinformatics*, 9(3):175–191, 2007.

[5] Chris Hill, Cecelia DeLuca, Max Suarez, and Arlindo da Silva. The architecture of the earth system modeling framework. *Computing in Science & Engineering*, 6(1):18–28, 2004.

[6] Darrel C Ince, Leslie Hatton, and John Graham-Cumming. The case for open computer programs. *Nature*, 482(7386):485–488, 2012.

[7] Irina Overeem, Maureen M Berlin, and James P M Syvitski. Strategies for integrated modeling: The community surface dynamics modeling system example. *Environmental Modelling & Software*, 39:314–321, 2013.

[8] Scott D. Peckham, Eric W. H. Hutton, and Boyana Norris. A component-based approach to integrated modeling in the geosciences: The design of csdms. *Computers & Geosciences*, 2012.

[9] James P M Syvitski, Eric W H Hutton, Mark D Piper, Irina Overeem, Albert J Kettner, and Scott D Peckham. Plug and play component modeling - the CSDMS2.0 approach. In *Proceedings of the 7th Intl. Congress on Env. Modelling and Software, International Environmental Modelling and Software Society (iEMSs)*. San Diego, CA, 2014.