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Environmental model access and interoperability: The GEO Model Web initiative

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ABSTRACT

The Group on Earth Observation (GEO) Model Web initiative utilizes a Model as a Service approach to increase model access and sharing. It relies on gradual, organic growth leading towards dynamic webs of interacting models, analogous to the World Wide Web. The long term vision is for a consultative infrastructure that can help address "what if" and other questions that decision makers and other users have. Four basic principles underlie the Model Web: open access, minimal barriers to entry, service-driven, and scalability; any implementation approach meeting these principles will be a step towards the long term vision. Implementing a Model Web encounters a number of technical challenges, including information modelling, minimizing interoperability agreements, performance, and long term access, each of which has its own implications. For example, a clear information model is essential for accommodating the different resources published in the Model Web (model engines, model services, etc.), and a flexible architecture, capable of integrating different existing distributed computing infrastructures, is required to address the performance requirements. Architectural solutions, in keeping with the Model Web principles, exist for each of these technical challenges. There are also a variety of other key challenges, including difficulties in making models interoperable; calibration and validation; and social, cultural, and institutional constraints. Although the long term vision of a consultative infrastructure is clearly an ambitious goal, even small steps towards that vision provide immediate benefits. A variety of activities are now in progress that are beginning to take those steps.

1. Introduction

Climate change, land use change, and changes to the world's aquatic systems are rapid, massive departures from recent historical norms that directly impact many Earth system processes (e.g. Barriopedro et al., 2011; Millennium Ecosystem Assessment, 2005). Interdependencies between these complex processes further complicate the situation (Gaber et al., 2008). Despite the significance to humans in terms of infrastructure, societal operations, and the ecosystem services upon which society depends, our ability to model, predict, and understand the impacts of these changes is very limited (National Research Council, 2002; Service, 2011). This problem is compounded by the limited access that decision makers have to the models, predictions, and related knowledge that do exist. As a result, these decision makers do not have all the information needed to develop appropriate response plans or to evaluate mitigation or adaptation options, despite the urgent need for better approaches to understanding these pending impacts (Gaber et al., 2008).

While this unfortunate lack of predictive capability exists to varying degrees and for a variety of reasons in different Earth science disciplines, it is perhaps particularly true for ecology and related application areas (EEA, 2008). There are several contributing factors, including missing observations to drive the models, incomplete scientific understanding of the processes involved, and limited computing resources. One more factor—limited interaction between existing models—is also important: despite many excellent models, these often work in isolation, without communicating with other models, even those within the same discipline. To highlight this isolation, models and their outputs are often said to be in "silos", a problem frequently cited for data (e.g. Esty and Rushing, 2007; Hey et al., 2009). This results in part because model source code is typically not shared (Barnes, 2010), but also simply because most models were developed independently and were never designed to interoperate with other

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models. Thus, although many ecological and other Earth system processes interact with one another, the models that represent them often do not. This is an important limiting factor in our ability to predict the impacts of change, particularly for ecological impacts.

One exception to this is the climate modelling community which, particularly in the last decade, has been working together to develop modelling systems that support the interaction of major components such as ocean and atmosphere (e.g. the METAFOR project[1]). This community has also taken steps to ensure that the outputs of those models are accessible (e.g. PCMDI: Program for Climate Model Diagnosis and Intercomparison[2]). Other Earth science disciplines may be less advanced in both access and interoperability, though to varying degrees. For example, although ecology has been building tightly coupled, integrated model systems—very useful ones—for some time, nearly all these systems are essentially large silos. There are good reasons for this, such as the complexity of the processes involved, and only fairly recently has ecological science and computational technology advanced enough so that model interoperability has become a limiting factor. On the other hand, hydrological processes are much better understood and this field has made good progress in developing modelling systems that utilize independent but interoperable models (e.g. the OpenMI Association[3] and CUAHSI Community Hydrologic Modeling Platform: CHyMP[4]) (Huang et al., 2011). In any case, interoperability remains a significant challenge for both of these as well as many other Earth science disciplines, and accessibility to models remains nearly universally limited (Barnes, 2010). Increased access to and interoperability between models has many benefits (Gaber et al., 2008) and will greatly enhance our ability to understand the impacts of change—and thus of society's ability to assess, mediate, and respond to those impacts.

There are a variety of approaches to address these challenges to access and interoperability. From a technical perspective, there are many benefits to moving from isolated, monolithic modelling systems towards open, modular, service oriented systems (Nativi and Fox, 2010) (Granell et al., 2010). For example, such an approach can provide a persistent set of independent services that can be integrated into a variety of more complex systems (Foster and Kesselman, 2006). And the recent revolution in information and communication technologies—e.g. MDA (Model Driven Architecture), SOA (Service Oriented Architecture), semi-structured data model and encodings, etc.—provides the basis for making significant steps towards these flexible platforms. From a social or community perspective, for extremely large and complex models such as those focused on global climate that require tight integration and operational co-location, a community-based approach works well (Voinov et al., 2010), particularly when coupled with interoperability-enhancing mechanisms such as the Earth System Modeling Framework (ESMF).[5] Virtual modelling environments that facilitate model–model (and modeller–modeller) interaction and access, such as the NASA Earth Exchange (NEX; Nemani et al., 2011) are another good approach, particularly for larger models, models with massive outputs, or for modellers that have only limited hardware resources. The focus of this paper, however, is the GEO Model Web Initiative (also referred as Model Web), a concept with both technical as well as social and community aspects. And although it is discussed in the context of environmental models, the approach and concept are general enough to apply to many disciplines.

2. The Model Web Initiative

2.1. Overview

The Model Web is a generic concept for increasing access to models and their outputs and to facilitate greater model–model interaction, resulting in webs of interacting models, databases, and websites. Integrating models into more complex, tightly coupled model systems has been done for decades and has led to great progress in predictive capabilities (Gaber et al., 2008). And although the idea of bringing together independent models to form loosely coupled model systems has existed in various forms for some time, technological challenges and other constraints have limited progress. It is perhaps only recently that the idea was formalized as the "Model Web" by Geller and Turner (2007) and Geller and Melton (2008). Advances in technology have made this possible and, at the same time, its importance has increased because of the critical need to improve capabilities that assess the impacts of climate and other changes.

The concept of model access by Web services, called "Model as a Service" (MaaS) has been around for several years (Geller and Turner, 2007; Geller and Melton, 2008; Roman et al., 2009); and model interfaces have been designed and tested to expose the models as web services (Goodall et al., 2011). The Model Web utilizes MaaS, relying on Web services to make models and their outputs more accessible, to foster interoperability, and to work towards the larger vision of systems of independent but interacting models.[6] This will facilitate the gradual development of a dynamic web of models, analogous to the WWW, integrated with databases and websites to form a consultative infrastructure where researchers, managers, policy makers, and the general public can go to gain insight into "what if" questions. That, in fact, is the Model Web vision. It will, for example, support natural resource managers and policy makers needing information on possible impacts of climate and other changes as well as alternative management options. And it will benefit researchers by making it easier to run model experiments and model comparisons or ensembles, as well as help highlight areas needing further development. The Model Web vision presented here is ambitious and long term, and can only be gradually converged upon. However, although it won't be fully realized in the immediate future, every model whose access is increased is a step in the direction of that vision and will have immediate benefits. As discussed in Section 5.2, experiments addressing specific challenges of the Model Web vision have been conducted in a variety of programs; these provide concrete and practical elements which help demonstrate the feasibility of the Model Web vision.

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[1] http://metaforclimate.eu/.

[2] http://www2-pcmdi.llnl.gov/.

[3] http://www.openmi.org.

[4] http://www.cuahsi.org/chymp-20090331.html.

[5] http://www.earthsystemmodeling.org/.

[6] A system of interacting models need not use Web services but could exchange information in a variety of ways including ftp, file sharing, and customized APIs. For example, for models exchanging large volumes of data, or with many cross-model iterations, other means of exchanging information may be more suitable. This "heterogeneous Model Web" is important but outside the scope of this paper.

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Model Web Vision

A dynamic web of models, integrated with databases and websites, to form a ***consultative infrastructure*** *where researchers, managers, policy makers, and the general public can go to gain insight into "what if" questions.*

The Model Web concept is being developed within the framework of GEO (Group on Earth Observations) and GEOSS (Global Earth Observation System of Systems; GEOSS, 2005) as a specific task (GEO, 2009) led by NASA, IEEE, the European Commission, and the National Research Council of Italy (CNR) (Khalsa et al., 2009, 2007; Nativi et al., 2009, 2007; Nativi, 2009a, 2009b). GEOSS is a logical home for such a concept because the observing, modelling and other systems that contribute to it, which come from a great many sources, must be interoperable.

2.2. *The Model Web Basic Principles*

The WWW is based on several simple, basic principles that facilitate organic and opportunistic growth, and these are largely responsible for its success. In a very real sense the Model Web is a WWW for models, so it is logical to base the Model Web concept upon similar principles, also designed to facilitate implementation and growth. These principles are:

1. Open access: One of the key reasons the Web is so successful is that the design imposes no constraints on who is allowed to create, or to access, a web page. Similarly, in the Model Web concept, anybody can create a service to share their model—it becomes simply another resource accessible via the Web—and anybody (or any machine) can access it.
2. Minimal barriers to entry: Another key reason for the success of the Web is the ease of publishing new resources: standardized, straightforward protocols and free tools encourage participation. User access to those published resources is even easier—all that is needed is a web browser and an Internet connection. Along with the explicit references between the resources (hyperlinks), this has made the Web extremely attractive as a general-purpose information system. Similarly, the Model Web seeks to minimize the entry barriers of both resource providers (modellers who share their model via Web services) and users (other modellers who desire input for their model, or end users on a website).
3. Service-driven approach: Model access is provided by services (i.e. Web services), making the Model Web a subset of a general-purpose distributed services framework (i.e. the WWW) and Model Web resources are a specialization of generic distributed resources (i.e. WWW resources).
4. Scalability: The design of the Web makes it completely scalable, a critical factor to its explosive growth. Scalability is important to the Model Web, and also inherent in the concept because it is based on Web services.

3. The Model Web architectural context

The Model Web can be implemented using a variety of architectures and frameworks, and any approach, or mix of approaches, satisfying the Model Web principles could be adopted to implement it. In this section five characteristics are suggested that will influence and facilitate Model Web development while keeping it compliant with the GEOSS architectural framework. Fig. 1 shows the overall ModelWeb architectural context, utilizing these five characteristics represented in UML notation.[7]

3.1. *Distributed System*

Because the Model Web is inherently distributed, model descriptions, instances, and related resources can be deployed, in principle, anywhere on the Internet. This characteristic allows for independent development of models and their services, by any model developer that chooses to participate, and thus supports organic and opportunistic growth. It also facilitates model sharing and interaction between models that are physically distant. And like all distributed systems it has the potential to be inherently resilient (though the actual level of resilience will depend upon how various services are provided). The distributed systems engineering helps to achieve the required scalability. Consistent with a distributed approach, in the Model Web vision the model developer decides what services to provide (these are not necessarily all those that their model is capable of providing), and whether to expose outputs of model subcomponents.

3.2. *System of Systems*

A System of Systems (SoS) may be defined as a collection of task-oriented, autonomous, and distributed systems that pool their resources to obtain a new, more complex, "meta-system" (Jamshidi, 2005). The components of an SoS must not only operate properly within the SoS, but must also operate independently to produce products or services satisfying their customer objectives and supporting but not supplanting their mandates (Butterfield et al., 2008). The component systems may be connected by implementing one or more interoperability arrangements that do not require tight coupling or strong integrations. This allows an SoS to maintain its inherent operational character even as system components join or disengage from it. Just like GEOSS, which will be an SoS consisting of existing and future Earth observation systems (GEOSS, 2005), the Model Web will also be constructed of both existing and new systems as those are added. System of Systems engineering improves scalability and helps lower entry barriers, making it easier to participate in the Model Web without major changes or the need to build entirely new systems.

3.3. *World Wide Web (WWW)*

As discussed in Section 2.1, the Model Web is a WWW for models, and the architectural and technological solutions developed in the context of the Web are highly relevant. The basic principles of the Model Web: Open access, minimal barriers to entry, service oriented approach, and scalability, are taken from the Web, though applied in a modelling context.

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[7] http://www.omg.org/spec/UML/.

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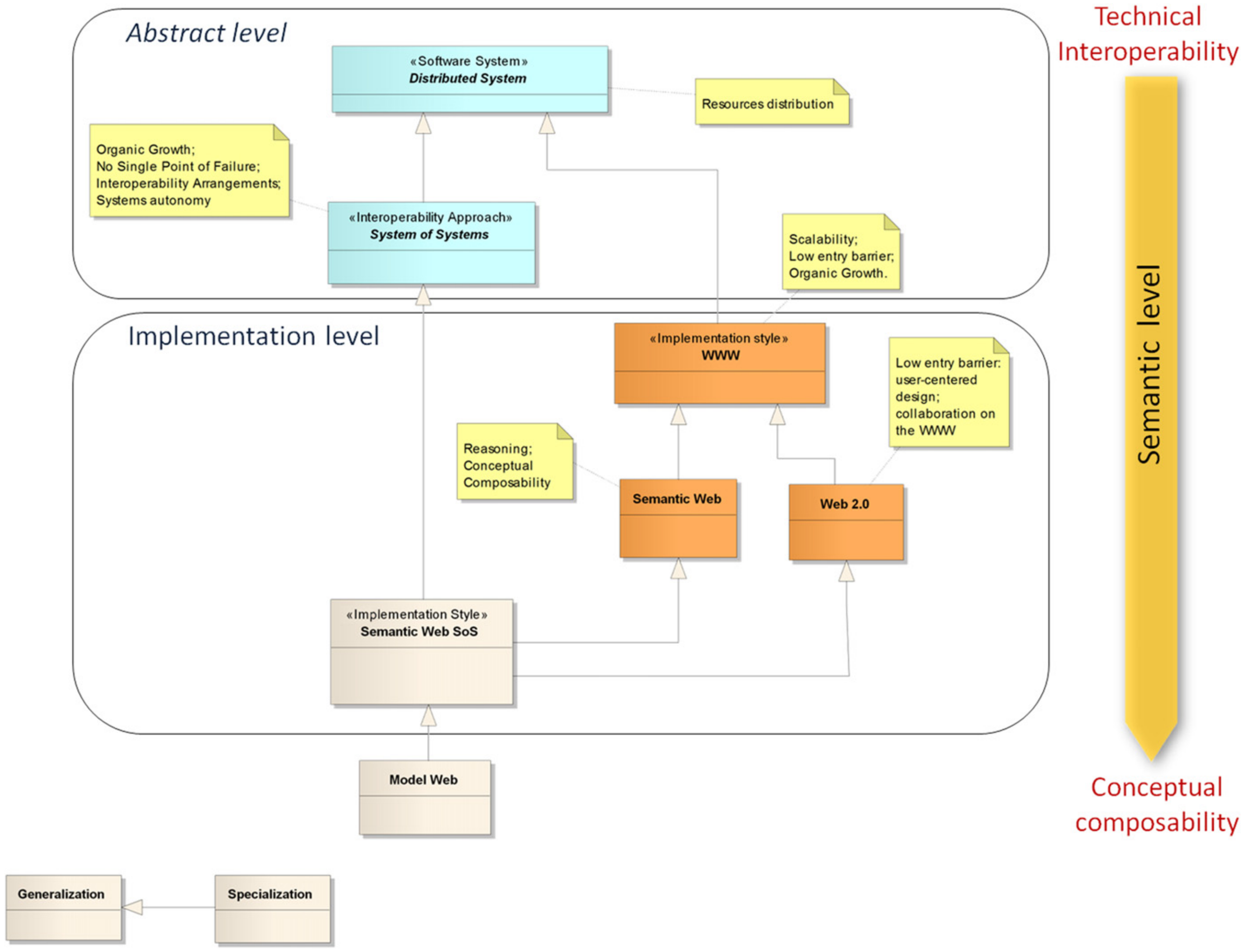

Fig. 1. The Model Web architectural context (using the UML notation).

3.4. Semantic Web

The "Semantic Web" is WWW creator Tim Berners-Lee's future vision for the WWW (Berners-Lee, 2001). It is based on the content-oriented description of digital documents with standardized vocabularies that provide machine-understandable semantics. In the Semantic Web the relationships among the data are defined and made available; the result is the transformation from a WWW of simple links into a WWW of meaning. The collection of Semantic Web technologies (RDF,[8] OWL,[9] SKOS[10], SPARQL,[11] etc.) provides an environment where applications can query the data, draw inferences from it using vocabularies, and perform other powerful activities (W3C Semantic Web), including models semantic annotation (Villa et al., 2009) to promote the reuse of environmental models (Athanasiadis et al., 2006). For the Model Web, Semantic Web technology will provide the "understanding" needed for conceptual composability instead of just technical interoperability.

3.5. Web 2.0

Interactive encyclopedias, blogs, and mash-ups are all examples of Web 2.0 applications. The term "Web 2.0" was coined by Tim O'Reilly (O'Reilly, 2005a, b) and although the term is now often used very broadly, Web 2.0 applications generally have many of the following characteristics: user-centred design; Web as platform; collaboration; crowd-sourcing; decentralized control; dynamic content; and Software as a Service (SaaS). The Model Web concept also incorporates many of these characteristics, and it is useful to think of it as a Web 2.0 application. The Web 2.0 approach and technologies may help, for example, to lower entry barriers and to facilitate user-friendly and collaborative interactions within the Model Web.

4. Towards a Model Web implementation: addressing key challenges

A variety of different architectures can be designed and implemented that meet the Model Web Basic Principles, and it is expected that the realized Model Web will be a mixture of these. All of them, however, face similar key technical challenges, and Sections 4.1 and 4.3 describe four of these and how each can be addressed. Although this paper focuses mainly on those technical challenges, non-technical challenges are also important and the most important ones are discussed in Section 4.2.

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[8] Resource Description Framework; http://www.w3.org/RDF/.

[9] Web Ontology Language; http://www.w3.org/TR/owl-features/.

[10] Simple Knowledge Organization System; http://www.w3.org/2004/02/skos/.

[11] SPARQL Query Language for RDF; http://www.w3.org/TR/rdf-sparql-query/.

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4.1. Technical challenges

The four key technical challenges are:

1. Information modelling: Environmental model sharing is a complex task involving several different entities. Model descriptions, model instances, model engines and model services are all examples of resources involved in the environmental model sharing process. Therefore, to establish an effective conceptual framework, relevant entities and their relationships must be clarified by defining an information model for the Model Web.
2. Minimal interoperability agreement: To support the growth of the Model Web as predominantly organic and opportunistic (Geller and Melton, 2008), which allows connection of environmental models and their services in arbitrarily complex ways, special interoperability arrangements are needed. However, these should be minimal (both in complexity and number) so as to minimize constraints on model providers and conform to the low entry barrier principle. This means that minimal agreements should be defined for environmental model description (for discovery), environmental model services interface (for access), and data formats and encodings. To address the problem of complexity without imposing constraints on both the user and providers, specific mediation services must be included in the architecture. These address issues such as data format conversions, semantic augmented discovery, and model chaining[12] (Villa et al., 2009).
3. High performance: Environmental models and their compositions are often complex, requiring a large amount of storage and/or processing resources. Integration with existing or planned Distributed Computing Infrastructures (DCI) such as Grids, Clouds and High Performance Computing (HPC) systems should provide the required capabilities. However, the Model Web concept is independent of where compute resources come from, and as a distributed system it is expected that resource needs will be met by multiple means in a seamless way.
4. Long term access: Environmental Models within the Model Web will be described in several different ways (documents, code, etc.) and will be finally accessed as a software implementation in the form of a running service. However, as the dominant computing technologies evolve both the document formats and the environments within which a model executes will change. This poses problems for long term access since the model's documentation and services will need to be maintained, yet the resources and the incentives for such maintenance may not always be in place. Model Web implementation should be able to leverage the existing solutions for long term preservation of documents and software artifacts.

Each of these four challenges will be discussed in Section 4.3, focussing on how they can be addressed in a Model Web implementation.

4.2. Other key challenges

4.2.1. Model-related challenges

Science does not have complete knowledge of all Earth processes, perhaps particularly ecological ones, and this limits what can be modelled as well as model accuracy. Another limitation for most models is that they require empirical measurements as inputs, yet obtaining such data can be difficult and expensive. While both of these challenges are inherent to modelling, they are not inherent to the Model Web concept *per se*, and the number of useful models that could interact in the Model Web is already large and will only increase. However, the volume of current scientific knowledge is vast and there are a great number of useful models, even if access to most of them is very limited. Increasing that access would greatly increase the value that could be extracted from them. The extensible nature of the Model Web makes it easy to add additional models as new science and models emerge.

More specific to the Model Web, and more serious, is that making existing, independently developed models interoperable is often difficult and expensive, for example, due to the dependencies between them. It is unlikely that such interoperability would arise without a focused effort and the substantial resources to support that effort. This is one reason that Model Web growth will likely be quite gradual. Validating and calibrating the resulting model systems, while essential to ensure meaningful and accurate results, can also be difficult and expensive (Voinov and Cerco, 2010). Furthermore, System of Systems implementations can demonstrate emergent behaviour, and this must be watched for and assessed to determine if such behaviour is an artefact of the modelling system. In the end, complex systems are inherently hard to build and maintain, regardless of the approach, so building Earth systems models, even when the major components already exist, will always be challenging (Voinov et al., 2010).

4.2.2. Cultural, social, and institutional challenges

A variety of social, cultural, and institutional challenges to the growth of the Model Web exist. One of these is the reluctance that some modellers may have to share their model—even though public funds are typically used for model development, a developer makes a very significant personal investment in their model, and seeks to obtain an appropriate return on that investment. Sharing a model or its outputs may allow someone else to generate results that the developer had hoped to generate. This problem is not unique to the Model Web, and has been discussed much elsewhere (e.g. Reichman et al., 2011; Science – Creative Commons). Resolution lies in ensuring that the appropriate incentives and rewards for sharing are in place. However, this is not necessarily easily done as it may involve cultural changes elsewhere, such as the criteria used by universities for advancement which are typically heavily weighted towards publication. Having said that, however, the authors' experience has been that many modellers want to share their models and/or their model outputs, and unwillingness to share has not been a limiting factor in model web growth.

Although the Model Web is a distributed system every model still needs a home. Models will probably most often reside at universities and government agencies, but support for the long term maintenance and operations of the computing infrastructure that models use tends to be limited and unreliable (Voinov et al., 2010), and varies from institution to institution. New approaches to funding this type of infrastructure are needed. Modellers who want to share their models and outputs face another challenge: sharing a model is not necessarily easy and often requires resources that are not provided by a sponsor. Or, they may have no desire to learn a new technology, such as how to share their model via Web services, or to implement all the recommended standards. For similar reasons documentation may also be limited, thus hindering the use of a model that is otherwise accessible. These issues could be largely resolved if sponsors required, and provided the resources to support, the sharing of models and/or their outputs. This is a cultural change on the sponsor side, and one that is fortunately starting to accelerate (e.g. US NSF – About).

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[12] As used here, a model "chain" is not necessarily just a simple linear sequence of models but can also be a network of models.

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Another social challenge is the difficulty of cross-discipline collaboration. Although the need for more of this has recently been emphasized by many authors (e.g. Hunt et al., 2009), and a significant amount of such collaboration is occurring, much more is needed. This is especially true for environmental issues, which typically involve one or more social, economic, or policy components and a variety of environmental components. In particular, more frequent inclusion of the social components when studying environmental issues is needed (International Council for Science, 2010; Nobre et al., 2010), as it is these social components that are most often driving the environmental change under study. Unfortunately, many environmental studies omit the social side, either because it is difficult enough just to study the various environmental components and their interactions, or because collaborating with social scientists is culturally distant. Fortunately, various sponsoring organizations, such as the US National Science Foundation, have begun to direct funding towards enhancing the level of collaboration, including with the social sciences.

4.3. *Proposed solutions to technical challenges*

4.3.1. *Information modelling*

The domain information model is a view of all the objects and concepts that make up the modelling information system realm. It captures the significant entities and concepts of the modelling systems domain and shows their relationships. This section will discuss a general conceptual framework introducing the environmental *Model* concepts and metadata entities necessary to share such an interoperability framework.

4.3.1.1. The conceptual framework. A simplified version of the Model Web conceptual framework is depicted in Fig. 2 (The conceptual schema language used for Figs. 2–4 is the Unified Modeling Language UML[13]; Booch et al., 1999; Fowler, 1997). A given *Application* may access an environmental model – i.e. the representation of a Model, here formalized by the *ModelRepresentation* entity (see Fig. 3). The *Application* can access the *ModelRepresentation* object through a Web *Service*. That is, the *ModelRepresentation* entity is a digital resource accessible as a *Service* – i.e. model as a service.

The *ModelRepresentation* entity is associated with one or more runs (i.e. *ModelRun* entity) which may generate either another *ModelRepresentation* object or one or more *Dataset* objects.

For the Model Web, the *Application*, *Service*, and *Dataset* entities are identified elements registered into GEOSS.

The *ModelRun* entity represents a run of a given model; this is the pivotal entity of the information model describing the environmental Model resources.

4.3.1.2. The environmental model resources. A simplified version of the data model for environmental *Model* resources is shown in Fig. 3.

The abstract *Model* entity represents the conceptual and mathematical structure of an environmental model. A model may be characterized (i.e. configured) by a set of *ModelParameter* entities. A *Model* is encoded by one or more *ModelRepresentation* objects and instantiated by one or more *ModelRun* objects.

The *ModelRepresentation* entity is a representation of a given model. Examples of model representations are conventional programs—they specify a set of instructions to follow or a set of procedures to execute. Each computer program may be considered as a representation of a model entity. In contrast with procedural representations, other possible instances are declarative representations—they specify the model elements, variables, and the functional relationships between them (Villa et al., 2009). The framework actually does not pose any limitation on the modelling graph represented by the *ModelRepresentation* entity.

A *ModelRun* launches an executable encoding of the *Model*, which is instantiated by a *ModelRepresentation* object. For input information a *ModelRun* may need: (a) one or more *ConfigurationParameter* objects; (b) one or more *InputData* objects. The *ConfigurationParameter* entity depends on the *ModelParameter* entity.

A *ModelRun* is executed by a *ModelEngine* object. In fact, the *ModelEngine* entity represents a tool or a framework which is able to carry out model runs.

The *ModelRun* entity generates one or more *ModelOutput* objects. A *ModelOutput* entity may either be a *ModelRepresentation*`s object or many *Dataset* objects.

4.3.1.3. The metadata. In keeping with the Model Driven Architecture (MDA) approach for interoperability implementation, the entities introduced by the previous schemas must be described by means of a set of metadata fields. According to the System of Systems approach, the metadata schemas can be different as long as they contain the information to achieve the necessary interoperability arrangements. Therefore, Fig. 4 shows the metadata entities required to describe the concepts which are the subject of the interoperability arrangements:

- *ModelMetadata*
- *RunMetadata*
- *EngineMetadata*
- *DataMetadata*
- *ServiceMetadata*
- *ApplicationMetadata*

Some metadata, such as that describing datasets, services, and applications, are already well-defined and accepted in several domains. However, metadata describing a model, its execution, and the related execution framework are relatively new for many domains, and the Model Web initiative is focussing on this challenge. For some domains valuable initiatives exist, such as the Common Metadata for Climate Modeling Digital Repositories project (METAFOR) which aims to develop a Common Information Model (CIM) to describe climate data and the models that produce it in a standard way. METAFOR will address the fragmentation and gaps in availability of metadata for the climatology domain. For meteorology, TIGGE (THORPEX Interactive Grand Global Ensemble; WWRP – THORPEX, 2008) is addressing this challenge in the framework of WIS (WMO Information System; WMO, 2007). UncertWeb (The Uncertainty Enabled Model Web) is working on uncertainty representation which could be used to describe uncertainty propagation in environmental models. Advanced tools may use this information to help assess errors and accuracies of models in a chain. Moreover model metadata could provide annotations such as links to other relevant documentation including papers, technical reports, test results, and literature describing how the model works and how it has been used and evaluated.

4.3.2. *Minimal interoperability agreements*

For multi-national and cross-domain SoS's handling Earth system science resources, it is impractical to build a monolithic data system to manage all data, and a Service Oriented Architecture (SOA) is a more appropriate technology (GEOSS, 2005;

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[13] OMG/UML, UML Notation. Available at http://www.omg.org/uml.

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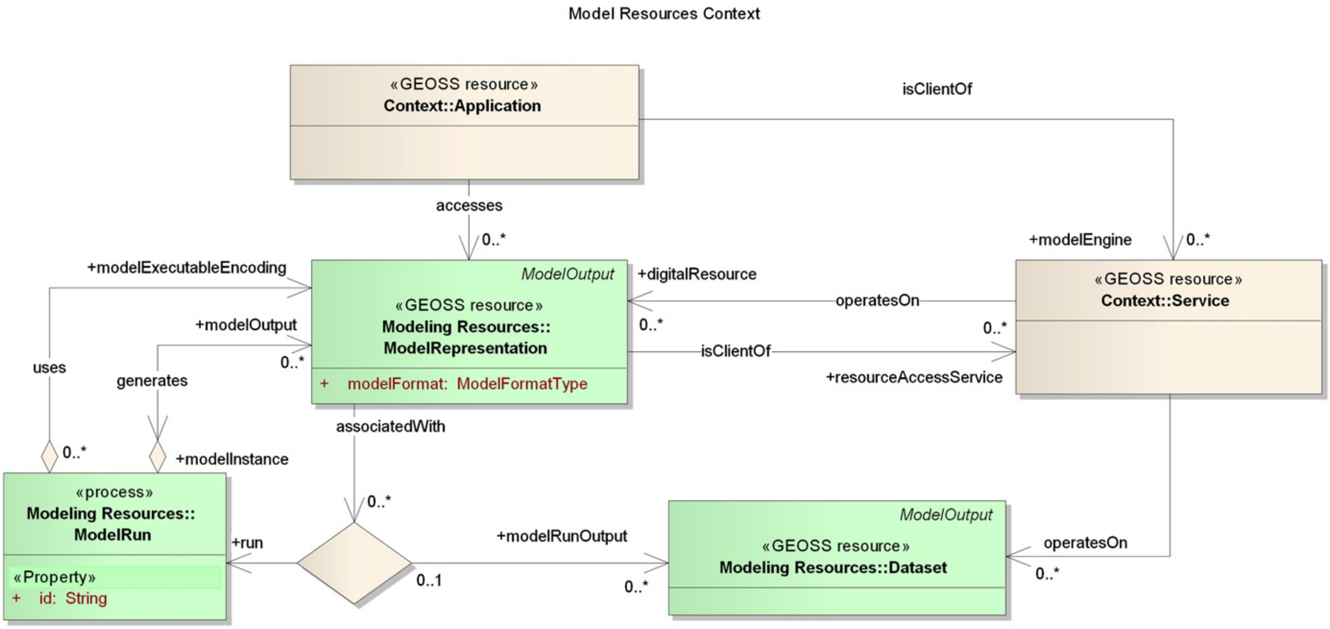

Fig. 2. Model web conceptual framework.

GEO, 2009; Ó Tuama et al., 2010). SOA is based on the notion that it is beneficial to decompose a large problem into a collection of smaller, related pieces. Services act as “black boxes” hiding their details from the outside world (WMO, 2007). Interactions can then take place according to agreed to interoperability technologies that should be based on non-proprietary, open standards. International initiatives seek to recognize standard specifications agreed to by consensus, with preference given to formal international standards such as ISO[14] and Open Geospatial Consortium (OGC).[15] Where non-standard specifications are widely adopted by Communities of Practice, some specific agreement for interoperability can be based upon them, as happens with the Special Interoperability Arrangements in GEOSS.

However, SOA raises three important interoperability challenges (Schroth and Janner, 2007; Schroth, 2007; Schroth and Christ, 2007): (a) semantic interoperability, which is particularly pertinent to the use of SOA in complex infrastructures that cross organizational or domain boundaries; (b) the heterogeneity and complexity of the Web Services stack, an impediment inherent to SOA, which is a rather complex technology mainly focused on implementing machine-to-machine connections; and (c) the existing gap between human users and machines, since SOA lacks intuitive human-guided service interaction and composition.

Commonly, Web Services make use of XML schemas to define the structure of exchanged documents. However, these schemas do not capture most of the semantics of document elements. The same situation is present for WSDL (Web Service Definition Language, an XML dialect) and services description, where a well-used, semantically rich description is still lacking. Automatic discovery and composition of services cannot be realized unless the naming of service properties is unambiguously defined and thus machine-readable.

Unfortunately, many different standards have emerged in different SOA implementations, complicating the setup of inter-organizational SOAs because services cannot be loosely coupled (to allow seamless interoperability, the same Web Services protocol stack implementation must be used). Also, there is no widely accepted service broker or market place that enables the world wide search for services that match a user’s needs.

Normally, Web Services are used to automate machine-to-machine collaboration but these do not provide a human interface. And they cannot be easily found (existing registries are complex) or understood – interfaces are generally defined using XML schemas, which are for experts.

For the Model Web, it is important to keep entry level barriers low, particularly during the early stages (cf. Section 6). In fact, for sharing, discovering, accessing, and using (global) Model Web resources, stakeholders must be aware of and implement heterogeneous interfaces and share different structured representations (models) of published resources, information content semantics, and data use best-practices.

The introduction of broker components, implementing mediation services, seems a good solution to address the shortcomings of the archetypal SOA pattern (Bigagli et al., 2006). This solution outlines a SOA extended pattern defined as a Mediator-Based Information Systems (MBIS); this is also called a Brokering-SOA (B-SOA) approach (Nativi and Bigagli, 2009). In fact, proper handling of heterogeneity is central to the successful deployment of advanced discovery and access services by mediating metadata profiles as well as protocol bindings. B-SOA is depicted in Fig. 5.

Usually, the mediated approach relies on: a) the identification of articulation points around a particular heterogeneity boundary; and b) the implementation of adaptation logic, whose execution is delegated to a specialized and lightweight component, the Mediator (Wiederhold, 1992). According to this approach, data model integration can be easily achieved by adapting the source data model to the destination one before data exchange. In the information and communication technology framework this solution has been conceptualized as a structural design pattern, the well-known Adaptor pattern (Gamma et al., 1995). A pattern is a way of arranging software components to solve common issues and avoid the proliferation of adaptor components; a MBIS defines a specific – possibly virtual (i.e. not used internally) – federal model as a common ground where all participants’ interactions are materialized. This approach has been conceptualized as a behavioural

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[14] http://www.isotc211.org/.

[15] http://www.opengeospatial.org/.

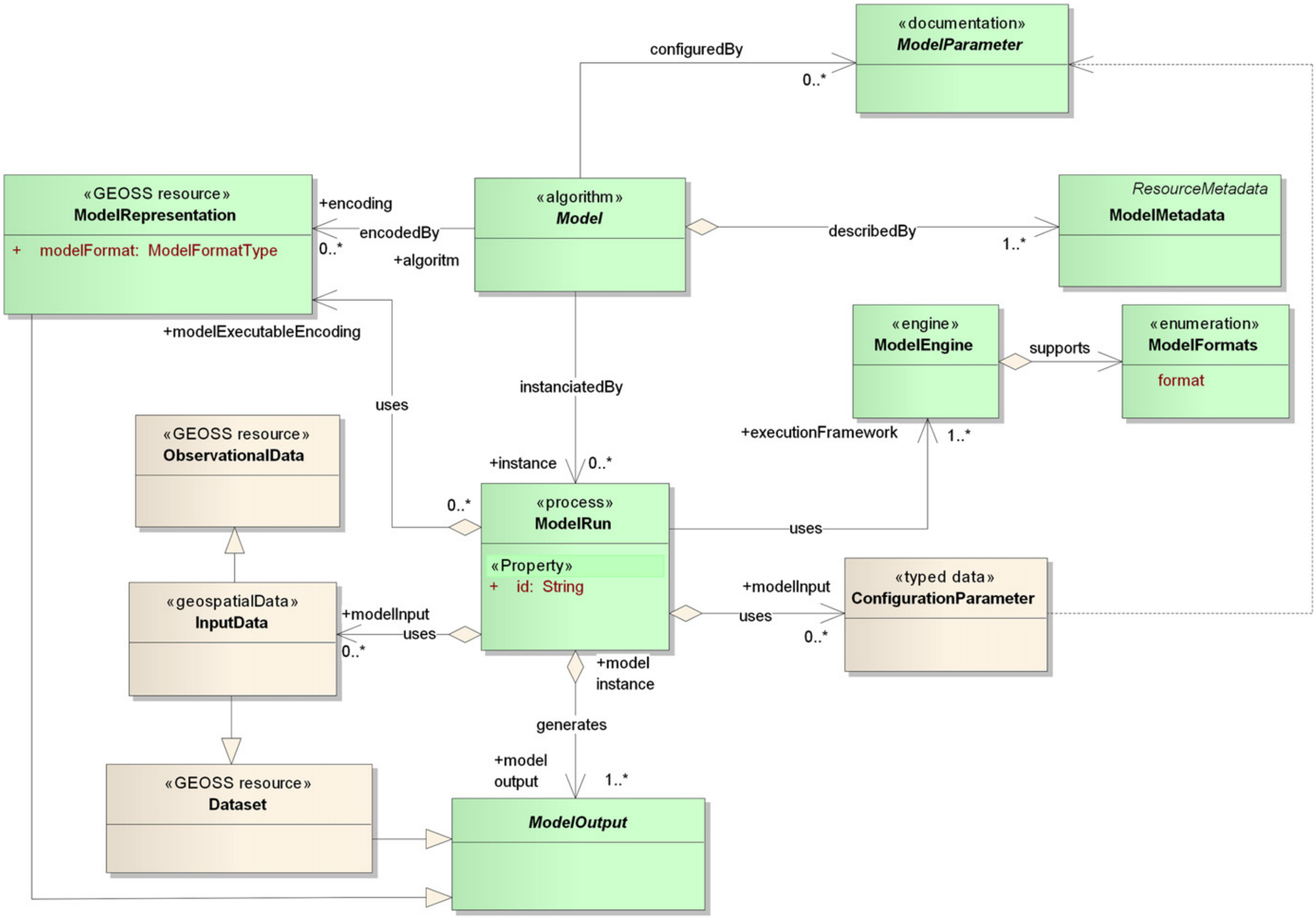

Fig. 3. The *Model* resources data model.

design pattern, i.e. a collaborative arrangement of software components in order to perform a task that no single component can carry out alone (the Mediator pattern; Gamma et al., 1995).

A broker component implements the necessary mediation functionalities – translating or interpreting message aspects (i.e. protocols and information model) and exposing the same service interfaces which would be invoked in its absence. Moreover, it also implements other advanced functionalities including distribution and messaging (Nativi, 2010). In this way, the broker is able to integrate multiple remote servers in an asynchronous way. Thus, discovery and access distribution are achieved by adopting a fully distributed environment, which is based on mediated message delivery to heterogeneous and remote discovery services, and results in aggregation.

The extended B-SOA approach makes it possible to: (a) minimize the interoperability agreements; (b) implement the necessary SoS flexibility by supporting present and future heterogeneity; (c) preserve component systems autonomy; (d) support conceptual composability; and (e) lower user entry barriers.

Although the B-SOA approach helps to shift the weight of mediation from the providers to the infrastructure, lowering the entry barrier, standardization as a means for achieving interoperability by reducing the heterogeneity is still important in the development of an architecture for the Model Web. Therefore it is important to coordinate with the relevant standardization bodies for the adoption and development of specifications. Such standardization should generally be pursued at levels where geospatial domain and scientific domains are considered, namely OGC, ISO, GEO and similar bodies. However it is clear that the Model Web vision touches several aspects going from basic communication tasks, such as events notification, to higher-level applications and semantics issues, like the definition of the information model, or the description of environmental models. Therefore it is expected that other standardization bodies may provide fundamental contributions. For example, the activities carried out by the W3C in the Semantic Web initiative and by OASIS[16] in the SOA domain are of fundamental importance. An investigation is required to evaluate if and how the Model Web specifications may leverage or contribute to the activities carried out in other contexts such as the Internet Engineering Task Force (IETF).

4.3.3. High performance challenge

Environmental model workflows may require a great amount of computing power and storage space for several reasons, including access to and processing of huge datasets (e.g. from satellite-based remote sensing); utilization of compute-intensive algorithms (e.g. for weather and climate forecasts); running large numbers of scenarios (e.g. in the study of climate change effects on the environment and ecosystems); the need for rapid response (as in disaster management applications), etc. Therefore performance, especially scalability, can be an important issue for an effective Model Web implementation. A Model Web

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[16] Organization for the Advancement of Structured Information Standards; http://www.oasis-open.org/.

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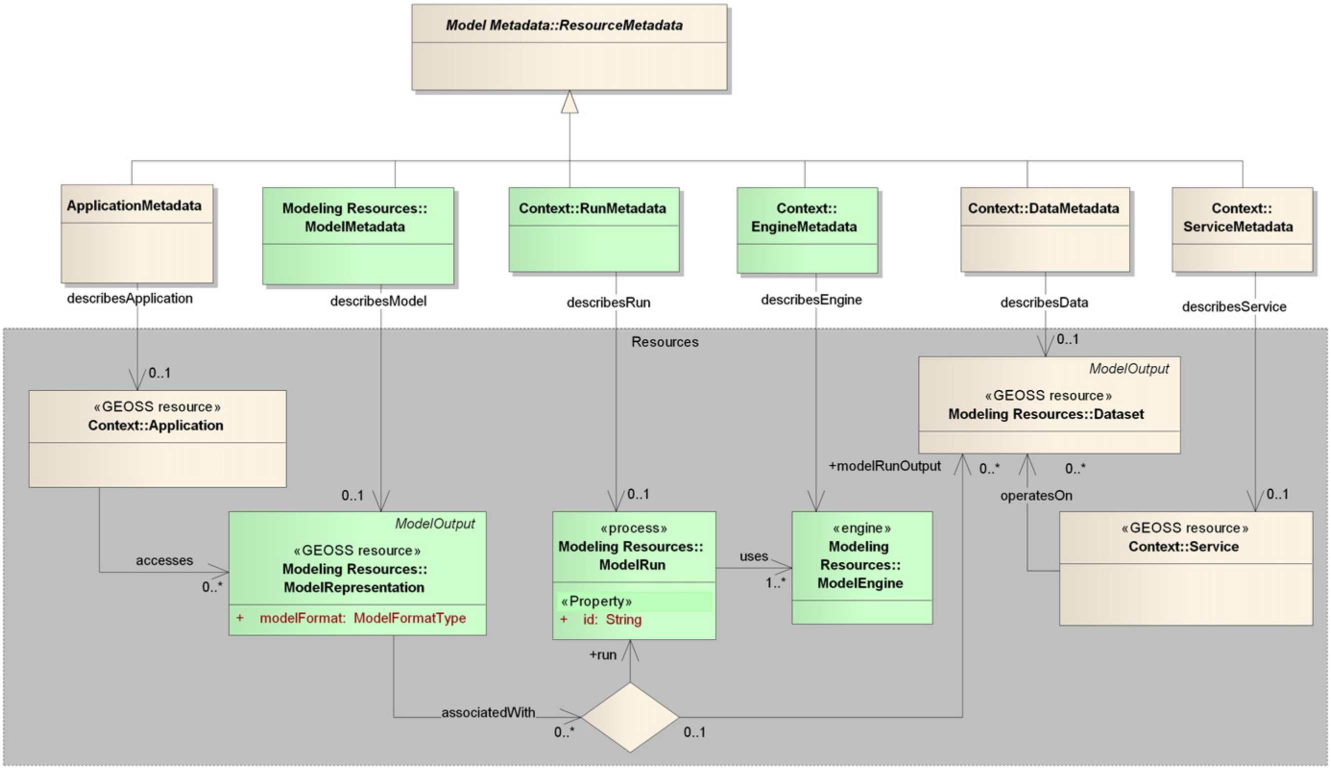

Fig. 4. Model web metadata framework.

implementation should leverage existing solutions and systems that have been proposed for so called High Throughput Computing (HTC) and High Performance Computing (HPC; Cossu et al., 2010; Renard et al., 2009). Indeed, since the advent of Information Technology HPC has been one of its most important objectives and drivers. In the last decades, several architectural and technological solutions have been proposed. Presently, the available solutions can be grouped into two main categories: stand-alone systems, which are based on powerful computing nodes (super-computers, clusters, and, recently, General-Purpose

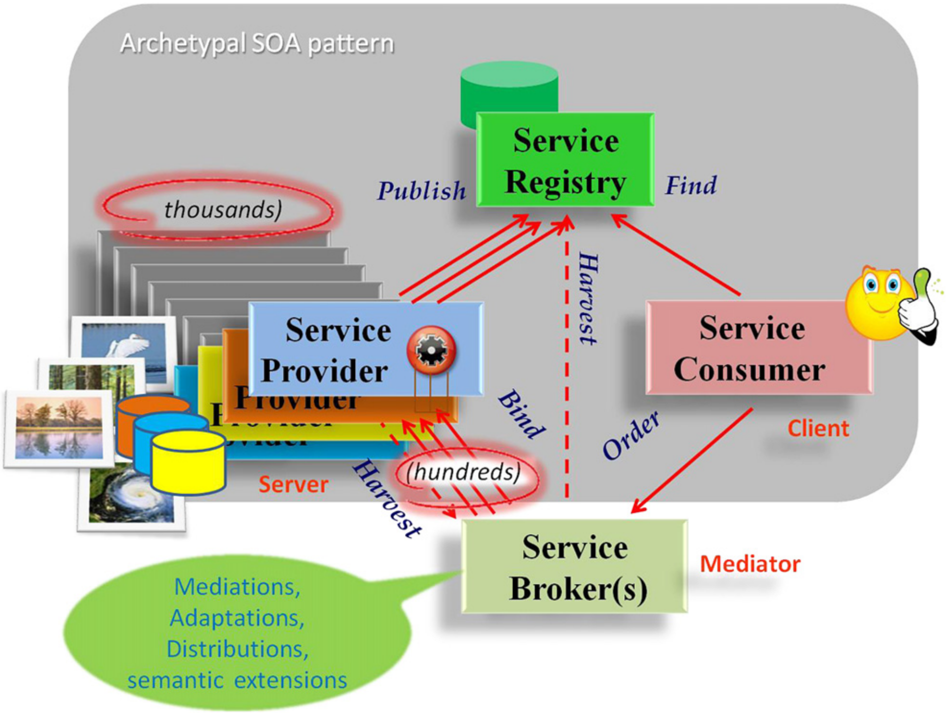

Fig. 5. The extended B-SOA pattern.

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Graphical Processing Units), and Distributed Computing Infrastructures (DCIs), such as Grids and Clouds that achieve high performance through the shared and coordinated access to multiple computing and storage resources (Buyya et al., 2009). They differ in terms of technologies, characteristics and business models, but any of them, depending on the specific use-case, can be used, in principle, to run environmental models and model workflows with high requirements of computing power and storage space.

However the integration of such infrastructure into the Model Web is not a trivial issue and it should be considered from the very beginning of the architecture design. In fact, a lot of literature is already available showing examples of environmental and Earth science model implementations on top of HPC systems and infrastructures. However the full integration of the Model Web with DCIs is more demanding. In the Model Web view, the user (human or machine) should interact with the models and model workflows in a homogeneous way whether they run on single machines or on complex DCIs. Therefore model and model workflows cannot be simply “ported” on top of a DCI, since, in this case, interaction with the specific tools and services of the DCI are required. Instead, in a Model Web view, a DCI should be integrated as one of the many autonomous systems, according to the System of Systems principle. This requires that they are accessed through specific services implemented on top of the DCI, and sharing the common interfaces, metadata and data models specified at the federation level of the SoS (Petitdidier et al., 2009). A simplified representation of such a services platform is depicted in Fig. 6, where the DCIs are hidden to the Earth System Science Services by an intermediate layer of Geospatial Information Services with different implementations for the different DCIs.

In recent years some experiments were carried out showing the possible integration of geospatial technologies and the DCIs, with particular reference to Grid infrastructures (CYCLOPS Project Consortium, 2008; Di et al., 2008; Foerster et al., 2011). These experiments provided implementation of standard geospatial services like the OGC Web Coverage Service (WCS) and Web Processing Service (WPS) making use of the DCI capabilities. The results are particularly valuable since these services are some of the fundamental building blocks for practical operation of the Model Web. However further research is required for a full integration of the DCIs in the Model Web. Indeed DCIs are usually self-contained infrastructures already providing functionalities that may overlap with similar functionalities of the Model Web, e.g. dataset and processes discovery, data access, etc. A harmonization of the respective architectures is needed to provide access to a DCI while keeping it autonomous. Moreover, to fully exploit the DCIs capabilities, the possible general approaches for the parallelization of environmental models should be investigated.

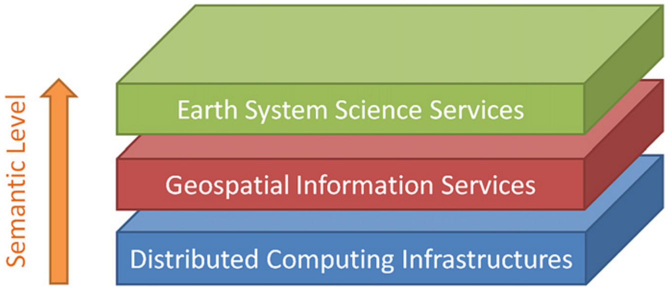

Fig. 6. Service layers for infrastructures interoperability.

Note, however, that the CPU cycles, storage, and bandwidth resources currently available are sufficient to support many models at useful resolutions and accuracies, and there are simple measures available to prevent users from exceeding available capacity. Model systems with particularly great resource needs, such as Global Circulation Models, can share standardized outputs rather than provide direct access to the models themselves. Thus, enhanced resource availability is by no means a necessary condition to begin building the Model Web. And it should be noted that, with the architectural caveats discussed earlier in this section, the Model Web concept itself is neutral with respect to where resources actually come from—that is a decision made by the individual model operators, of which there will be many in a distributed system such as the Model Web.

4.3.4. Long term access challenge

Long term access to models is typically either via registries that provide links to the original references (e.g. Register of Ecological Models (REM),[17]) or archives that provide access to the original source code and documentation (e.g. the ORNL DAAC Model Archive[18]). In both cases, associated metadata may support basic discovery functionality, however, to fully enable persistent access to models, more advanced solutions are needed (Thornton et al., 2005; DKRZ).

There are many ways that information technology changes over the time. For example, existing services might be discontinued; hardware and software platforms (operating systems, programming platforms, etc.) may evolve and lose compatibility with previous versions; and programming languages may deprecate instructions and libraries. Because such technological change can result in the loss of access to a valuable model, the provision of long term preservation capabilities should be considered in the architectural design of a Model Web implementation, building upon the existing solutions. Complicating the situation is the fact that environmental models (and model workflows) can be provided in either a declarative or in a procedural way (Muetzelfeldt, 2004) (Villa et al., 2009) and as various types of artifacts, such as: a formal description in a proper language (e.g. BPMN[19]); source code; executable code bound to a specific hardware or software environment; or even as a software service accessing a model instance deployed on a specific node. Moreover, the related technical and scientific documentation may be scattered among several sources, each with different formats and encodings.

In recent years significant effort has focused on the long term preservation of digital information, including software artifacts, and three main approaches have been proposed. The *technical preservation* approach maintains the original software (typically a binary) and, often, hardware of the original operating environment, almost as in a museum. The *emulation* approach re-creates the original operating environment by programming platforms and operating systems to emulate that original environment, allowing the original binary to run “as is” on a new platform. The *migration* approach transfers digital information to a new platform and recompiles and reconfigures the source code to generate new binaries, then applies them to the new environment, with updated operating system, languages, libraries etc. (Matthews et al., 2009). These three approaches differ in terms of effort, preserved characteristics (application performance, “look and feel”), and feasibility (either for technical reasons or for existing Intellectual Property Rights conditions). The best choice depends on the type of

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[17] http://ecobas.org/www-server/mod-info/index.html.

[18] http://daac.ornl.gov/models.shtml.

[19] Business Process Modeling Notation; http://www.bpmn.org/.

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software artefact to be preserved, so an important challenge for Model Web realization and long term access is assessing the best approach for preserving environmental models.

Two new approaches that could be applicable to the Model Web are now emerging. *Standardization* is a means for addressing interoperability by reducing the heterogeneity. In particular, metadata specifications (*ModelMetadata* in Fig. 4) may include preservation information according to existing standards like the Open Archival Information System (OAIS). *Virtualization* is an emulation approach where a virtual hardware/software platform runs on a different hardware/software platform through a virtual machine. One of the main drawbacks of the emulation approaches is the loss of “look and feel”, but for environmental models this might be acceptable. Moreover virtualization is an important trend in current IT, and is at the basis of Cloud Computing. Therefore virtualization applied to environmental models could be valuable both for preservation and deployment on-demand.

5. Relationships to other efforts

5.1. Existing frameworks

Recently, several approaches for integrated and interoperable modelling have been developed (Jakeman et al., 2008; Argent et al., 2005). The simplest consists of building tools for running selected simulations. A user interface such as a GUI allows the user to select the parameters and algorithms of the simulation, and to access and visualize the output. Such tools are often extensible and act on code that is open source. Sometimes it is possible to access the tool functions through an open service interface allowing integration with more complex chains, an approach adopted by, for example, OpenModeller (Souza Muñoz et al., 2011). This approach facilitates designs that are targeted to specific communities, however, it can be difficult to integrate the tools into more complex scenarios since useful capabilities for chaining, such as logging and event handling, may not be implemented. An interesting evolution of this approach is nanoFORGE/nanoHub which offers a broad variety of simulation tools that users can access from their web browser without installing software on their local machine (Klimeck et al., 2008), following the Cloud concept.

A different approach for interoperable modelling lies in the design and adoption of frameworks such as the Object Modelling System (OMS; Kralisch et al., 2005), ModCom (Hillyer et al., 2003), The Invisible Modelling Environment (TIME; Rahman et al., 2003), the Open Modelling Interface (OpenMI; Gregersen et al., 2007), the Spatial Modelling Environment (SME; Maxwell and Costanza, 1997), Tarsier (Watson and Rahman, 2004), Interactive Component Modelling System (ICMS; Rahman et al., 2001), Earth System Modeling Framework (ESMF; Hill et al., 2004), SEAMLESS-IF (Van Ittersum et al., 2008), and others. These differ in a variety of aspects, including domain scope (single vs. multi-disciplinary; Hennicker et al., 2010), functionality (model chaining vs. step-by-step simulations), and technology (single vs. multi-platform); such differences reflect the varying needs of the target communities.

Although these frameworks provide valuable functionality they also impose constraints on model developers and integrators, such as requiring a specific programming language or development/deployment platform. These constraints limit the breadth of application and can increase entry barriers; for example, legacy models may require major modifications before they can be included. And because such frameworks are usually closed environments, interoperability of spatially distributed models, or of models in different frameworks, can be difficult. The adoption of Component-Based Architectures (CBAs), embracing mechanisms and techniques for developing coarse yet reusable technical implementation units that are environment and container-aware, may help to overcome some obstacles in the interoperability. In a CBA, units of software are encapsulated as “components” which interact with other components only through well-defined interfaces. This approach allows the internal implementation of the component to remain opaque to the rest of the world, and presumably hides much of the complexity of the software. These more manageable units of software can be composed together to form applications; in many cases, well-designed components will be reusable across a number of different applications without internal changes (Larson et al., 2004). For example in the Common Component Architecture (CCA) the component specification enables code-sharing among disparate groups by defining a few simple rules that, when followed, allow plug and play compatibility with minimal impact on performance. In addition, the structure of the CCA is such that each application composed of CCA-compliant components will be itself a component. Moreover, the CCA working group realized that trying to dictate language preference to scientists was futile. This is why the CCA separates the abstract mechanism of connecting components from the underlying language binding (Armstrong et al., 1999). A further evolution is based on Service Oriented Architectures (SOA; Erl, 2009; Theisselmann et al., 2009). Here, models are exposed as services, thus moving the interoperability agreements from the technical environment to the interface specifications as in CBAs. But open standards such as SOAP/WSDL and OGC WPS help to abstract the resulting system from the technologies adopted for implementation, and support modelling on the Web. It is also possible to leverage experience from additional domains, such as e-Government and e-Commerce, where application workflow using BPMN/BPEL[20] solutions is a common task. This approach makes possible the integration of legacy systems and spatially distributed models in a way closer to the Model Web principles.

Moving from dedicated tools to technological frameworks and finally to CBAs and SOAs, the implementation of environmental modelling systems becomes less dependent on the underlying technology, thus contributing to the achievement of some Model Web Basic Principles, such as the minimal barrier to entry. However, even with SOA, publishing an environmental model requires the provider to focus on and understand some technological aspects; additional levels of abstraction are needed to further hide the underlying technology and continue to lower the barrier to entry. For example, a proper interface to the model must be designed and developed according to strict specifications (e.g. in SOAP or OGC WPS) and it is necessary to provide the service description in a register (either by directly publishing the description or by metadata harvesting from a service endpoint). This is different from the Web scenario, where publishing a document can be done without knowledge about how the Web works thanks to very light specifications and the intuitive concept of hyperlinks that enable navigation and crawling. Obviously, publishing a model is a more complex task, but the recent successes in the Semantic Web and Web 2.0, for example, may help to lower the entry barrier for model providers. According to the schema presented in Fig. 1, mediation tools, Web 2.0 mash-ups, and semantic descriptions might enrich traditional SOAs and help achieve the envisioned Model Web. A first step towards better support for the Model Web might be the definition of an abstract Web Modeling Service to be realized in different implementations. For example, in the OGC architecture such a service could be

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[20] Business Process Execution Language; http://www.oasis-open.org/committees/wsbpel/.

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implemented as a WPS 2.0 extension whose payload is the data model described in Figs. 1–3.

5.2. On-going activity

Model Web growth is still in the very early stages and only a very limited number of models are available as a service. However, there are several ongoing initiatives specifically contributing to Model Web growth at different levels, and these are briefly discussed here. These activities address a variety of Model Web challenges and provide practical experience to help guide Model Web development.

GEO pilots: As mentioned in Section 2 the GEO Model Web Task focuses on developing and promoting Model Web concepts and connecting with related efforts. The GEO Interoperability Process Pilot Project (IP3) and Architecture Implementation Pilot (AIP)[21] proof-of-concepts have developed some early prototype systems: IP3 developed two pilots about inferring the role of climate in the decline of endangered species (e.g. American pika) and in the spread of invasive species (e.g. Canadian butterflies) (Nativi et al., 2007). AIP phase two consolidated and extended the studies on the impact of climate change on biodiversity by developing a pilot on "modelling the arctic food chain" (Nativi, 2009b). These pilots developed and experimented with interoperability solutions for accessing IPCC outcomes and Ecological Niche Modeling (ENM) components. In AIP phase three climate change model outputs were used for habitat assessments and ecological forecasting (Dubois et al., 2011), and AIP phase 4 will consolidate this work and incorporate the eHabitat initiative (described later in this Section).

European Commission projects: The European Commission has funded several projects under its FP7 program to support GEOSS implementation; some of these have contributed to Model Web concept experimentation. UncertWeb,[22] for example, will enhance model discovery and the chaining of model services, quantifying uncertainty for analysis and modelling of real-world environmental systems (Cornford et al., in this issue). EuroGEOSS[23] has implemented the extended B-SOA pattern by introducing the *EuroGEOSS Brokering framework* for services discovery and access (Craglia et al., 2011). In its last phase, EuroGEOSS will leverage the UncertWeb model discovery and uncertainty descriptions to extend its multi-disciplinary operational capacity (in particular the discovery broker) which connects the European capabilities for the Biodiversity, Forestry, and Drought thematic areas; Hydrology, Climate, and Meteo-Ocean areas will be considered as well. EuroGEOSS has contributed another European Commission initiative playing a role in the model web: eHabitat. eHabitat is a Web service developed by the EC Joint Research Institute that computes the probability of finding ecosystems with properties similar to a particular area of interest (Dubois et al., 2011). It can be used to determine the uniqueness of a particular habitat, which has implications for land management. The EuroGEOSS discovery and access brokers are contributing to the advancement of the GEOSS Common Infrastructure (GCI) and will be further developed by the FP7 GEO-WOW project (starting in September 2011) for the Weather, Ocean biodiversity, and Water areas. The GEO-WOW project will facilitate thematic and multi-disciplinary applications through the development of a multi-disciplinary semantic-rich framework for the discovery and evaluation of data, services, and analytical models (GEO-WOW Consortium, 2010). For example, GEO-WOW will develop products for both operational weather forecasters and end users that will significantly reduce the amount of data that needs to be transferred and will ensure that end users do not need expert knowledge of either the specific meteorological processes or the contributing NWP models to use the products. The project will demonstrate the availability of ocean ecosystem variables and model outputs on the GCI, and the access and use of hydrological data in cross-disciplinary applications such as flood modelling and forecasting. The ENVISION project[24] aims to provide an infrastructure to support non-ICT-skilled users in the process of semantic discovery and adaptive chaining and composition of environmental services. In the context of the GEO/GEOSS Science and Technology roadmap,[25] the FP7 EGIDA project[26] focuses on interdisciplinary and inter-project communication and coordination; this is contributing to the dissemination of several of the ongoing initiatives and projects for environmental model integration.

NASA programs: NEX is a NASA-funded project that provides virtual modelling resources, including supercomputer access, to ecological and related models (Nemani et al., 2011). While not specifically using the Model Web concept, it is designed to facilitate model–model, and modeller–modeller interaction, and will lower the barrier to entry for modellers that want to make their models and outputs available as services. A key feature of NEX is that it includes access to the NASA Terrestrial Observation and Prediction System (TOPS) model outputs, with plans to provide access to the model itself as a service. TOPS is considered a "keystone" model because it produces outputs of use to a great many other models and users, and represents a model that should be made available early on during Model Web development. The Regional Ocean Modeling System (ROMS[27]), a physical oceanography model, is perhaps the marine equivalent of TOPS and would make another excellent keystone model. As for TOPS, access to ROMS is currently limited.

Other initiatives and programs: OpenModeller[28] is an open source project to support modelling the distributions of species based on their historical range and environmental variables, with the goal of providing web-based modelling services. eHabitat[29] helps assess the impacts of global change by identifying areas with similar environmental characteristics, and is in the process of being made available as a Web Processing Service in support of the Model Web concept. TOPS, ROMS, OpenModeller, and—since it was designed from the beginning to be provided as a service—perhaps especially eHabitat, are all examples of existing models that are excellent candidates for early participation in the Model Web.

Finally, a few broader efforts should be mentioned. The Community for Integrated Environmental Modeling[30] (CIEM) is a recently initiated community of practice that grew out of workshops and discussions by the US Environmental Protection Agency, the OpenMI Association, and other organizations over the last several years. It is focused on advancing the science of integrated modelling (Laniak, 2008) for all types of environmental applications, and a recent meeting led to the development of an implementation strategy (Rizzoli et al., in this issue). The Model Web concept is one of several approaches that facilitate integrated modelling.As mentioned in Section 2.1 the Model as a Service (MaaS) approach is being developed and promoted by a number of people and organizations (Roman et al., 2009). The standards

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[21] http://www.earthobservations.org/geoss_call_aip.shtml.

[22] http://www.uncertweb.org/.

[23] http://www.eurogeoss.eu/.

[24] http://www.envision-project.eu/.

[25] http://www.earthobservations.org/ag_stc.shtml.

[26] http://www.egida-project.eu/.

[27] http://ourocean.jpl.nasa.gov/.

[28] http://openmodeller.sourceforge.net/.

[29] http://ehabitat.jrc.ec.europa.eu/.

[30] http://iemhub.org.

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organization Open Geospatial Consortium (OGC) is constantly updating the web services upon which the Model Web depends, with Web Processing Service being of particular interest here. And the Committee on Earth Observation Satellites (CEOS) is promoting interoperability, through the Virtual Constellations concept, the Sensor Web approach (Usländer et al., 2010), and by facilitating model interoperability and access via the Model Web concept (GEO, 2010).

5.3. Role of the Model Web within GEOSS

The Model Web initiative is important to the observation and modelling objectives of GEO/GEOSS. For example, GEO advocates increased sharing of methods and capabilities for the modelling and analysis needed to transform data into useful products (GEOSS, 2005). Furthermore, models and the Model Web will support the harmonization of observations, real- or near real-time monitoring, integration of *in situ*, airborne and space-based observations through data assimilation and models, and early detection of significant and extreme events, all of which are crucial GEOSS activities. The establishment of global, efficient, and representative networks of *in situ* observations to support process studies, satellite data validation, and algorithm and model development will be encouraged, as well as the detection, documentation and attribution of change (GEOSS, 2005). Therefore GEOSS will support the research and development of models, data assimilation modules, and other algorithms that are able to produce global and regional products more effectively.

The Model Web infrastructure will significantly contribute to the GEOSS capacity building objectives which aim to facilitate: (a) access to data and models, particularly for developing countries; (b) use of Earth observation data and products following accepted standards; (c) analysis and interpretation of data to enable development of decision support tools and to advance understanding in the nine societal benefit areas (GEOSS, 2005). This infrastructure will employ the SoS approach, building on – and integrating with – the next generation of GCI (GEOSS Common Infrastructure), which itself will leverage several Model Web principles by utilizing some of the new technologies provided by the Semantic Web and the next Web generations (e.g. Web 2.0; GEO-WOW Consortium, 2010).

6. Development approach and sequence

Realizing the full Model Web concept is a long term activity and, as mentioned in Section 5.2, has barely begun. Although it is difficult at this early stage to predict exactly how it will unfold, something like the following scenario seems plausible.

In the beginning the limiting factor to a useful Model Web is participation of a sufficient number of models, so the highest priority must be to encourage participation and minimize barriers to entry. In fact, as a Basic Principle, low barriers to entry must be continuously maintained even as the Model Web matures or else it will stagnate. At the same time, because appropriate standards will lead to a more powerful, more useful, and more smoothly operating web, standards are also necessary, even though standards can increase the barrier to entry. This potential conflict can be addressed in two ways. First, standards should be kept at an appropriate level, whereby they are sufficient to facilitate operation of the Model Web, yet do not pose a large entry barrier. This is how the WWW is designed. Second, to keep entry barriers low the Model Web must accept a range of formalities and be as inclusive as possible. For example, when contributing a legacy model, a modeller might initially ignore most standards and just make her model, or model outputs, available as a service; standard vocabularies, for example, may be skipped. Although ignoring such standards can be abhorrent to many, it minimizes the barrier to entry. And those standards were ignored prior to the model being made available, the difference afterwards is that model access is greatly increased—a big step forward given that model sharing is currently extremely low (Barnes, 2010). Furthermore, it is expected that modellers will incrementally, over time, increase their use of standards, registries, and other infrastructure elements. This will make their lives easier by decreasing the number of questions they get from users, for example; it will also increase the number of users utilizing their model services because the models will be easier to use. The end result is that at any one time the Model Web will have a range of formality levels, initially tending towards the less formal but becoming increasingly formal over time.

7. Summary and conclusions

Because it utilizes a Model as a Service approach, the Model Web will increase model access and sharing, facilitate modeller–modeller and interdisciplinary interaction, and reduce reinvention. While it is difficult to quantify costs and benefits the Model Web will provide a loosely coupled framework to make reuse of existing services easier and so help reduce long term modelling costs. This will not only make more efficient use of limited model development resources, but by increasing the number of users it can result in more feedback to model developers and speed up model development. These are all very important benefits, however, the long term vision is larger and more ambitious: to develop a “consultative infrastructure”. This is a wide network of interconnected models, data, and tools accessible via websites that are available as a resource for decision makers, researchers and the general public.

To ensure a low barrier to entry for new modeller participants—one of the Basic Principles—the Model Web will not exclude participants if they do not adhere to recommended standards or use standard structures and tools. As a result, the Model Web will consist of models with a range of adherence to such standards and tools. However, the greatest utility will be realized as use of these standard items increases because this allows for enhanced discovery, easier paths to interoperability, and provides other advantages.

Much of the Model Web is being developed within the context of GEO/GEOSS and it will support a variety of applications there. However, because the concept is very generic it should not be viewed as isolated within GEOSS but rather as one with broad applicability. Also, the concept has much in common with that of Model as a Service and other concepts for model coupling, and there is considerable ongoing work by people and organizations with an interest in these. The open nature of the Model Web will make it easy for these various efforts to interact and further progress towards a consultative infrastructure.

Finally, there are a number of challenges to implementing the Model Web—some technical, some inherent to modelling, and some social, cultural, or institutional. The Model Web vision of a consultative infrastructure depends, among other things, upon models being made to interoperate, upon the generation of useful results, and upon appropriate websites with user interfaces designed for their intended audience. These are all significant challenges and addressing them will require significant resources. One reason the WWW has been able to grow so explosively is that it is easy to add a website to it; in contrast, adding a model to the Model Web will in most cases require somewhat more effort. But there are more similarities to the WWW than differences, and it is clear that the Model Web, like the WWW, is too complex to simply be designed and built; rather, it must be grown, organically and opportunistically, within guidelines and proper standards. For the

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Model Web, this means gradual convergence towards the vision of a consultative infrastructure. And every step towards that vision will improve society's ability to assess, predict, and respond to the impacts of change.

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