Providing global change information for decision-making: capturing and presenting provenance

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Short Summary: Global change information demands access to data sources and well-documented provenance to provide evidence needed to build confidence in scientific conclusions and, in specific applications, to ensure the information’s suitability for use in decision-making. A new generation of Web technology, the Semantic Web, provides tools for that purpose.

The topic of global change covers changes in the global environment (including alterations in climate, land productivity, oceans or other water resources, atmospheric composition and/or chemistry, and ecological systems) that may alter the capacity of the Earth to sustain life and support human systems [1]. Data and findings associated with global change research are of great public, government, and academic
concern and are used in policy and decision-making, which makes the provenance of global change information especially important. In addition, since different types of decisions benefit from different types of information, understanding how to capture and present the provenance of global change information is becoming more of an imperative in adaptive planning.

**Provenance tracking**

Many science issues in global change research are complex and yield multiple implications for management, such as sea level rise projections. In some cases, including in academic research and for broad scale policy discussion, it is useful to examine probabilistic estimates of future sea level rise (e.g. what is the ‘most likely’ amount of change over time), whereas in other instances, it is helpful to refer to a broader range of plausible sea level changes (e.g. risk-based framing for a wide variety of coastal management decisions). In 2013 the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) [2] examined four different greenhouse gas emissions pathways and associated projections of sea level rise. They concluded that it was ‘likely’ that global sea levels would be between 0.26 to 0.81 meters above recent levels by the last two decades of current century. As a comparison, a report published in 2012 by the National Oceanic and Atmospheric Administration (NOAA)’s Climate Program Office (CPO) [3] in support of the National Climate Assessment [4], provided a wider range of plausible sea level rise describing scenarios from 0.2 to 2.0 meters above 1992 levels by 2100.

The above two reports took different approaches for different reasons; the CPO report included higher and lower estimates of sea level rise because they were considered useful in risk-based decision-making even though the IPCC considered them less ‘likely’. In other words, awareness of low probability and high impact futures is useful for coastal decision-making, but arguably less valuable for broad scale policy framing. For limiting risk to life and property, it is therefore useful to understand the nature of the scenarios and projections, especially at the higher and lower end of the range. In order to do this it is
necessary to know what data, model, and analytical sources are used in each report and to be able to access them easily and in an interpretable format — a goal that provenance tracking can support.

The literal meaning of provenance is the origin or source of something. As discussed above, understanding the origins of global change information is not only critical to people’s understanding of how to use it, but also facilitates integration of knowledge across disciplines. This kind of interdisciplinary assessment is important in managing the risks associated with global change. For the above example, the AR5 and the CPO report provided textual descriptions for tracking the provenance of their projections but the descriptions are relatively technical and not easy to interpret in terms of what is ‘best’ or most appropriate in any given circumstance. A more useful approach, in the long term, is to provide search options that facilitate access to data and allow traceability back to original sources, authors, programs and even observing systems.

Although provenance tracking is useful and important, as shown by the above example, capturing and presenting provenance is not an easy task. In scientific works documenting provenance includes linking a range of observations and model output, research activities, people and organizations involved in the production of scientific findings with the supporting datasets and methods used to generate them [5]. It requires significant effort to identify, extract, link, and assemble pieces of information from accumulated documents, codes, datasets, and so on.

**Categorization and annotation**

The root of provenance capture grows from the soil of metadata collection. Metadata are data about data. Traditionally seen in library catalogs, metadata have received significant attention in the last decade and several metadata standards have been developed to address the recent data deluge challenge. One widely used standard is the Dublin Core metadata schema [6], which consists of 15 core elements, such as title, creator, subject, description, publisher, and so on, that can be used to describe a resource. The schema is
simple, which is an advantage for use. However, it is also a weakness because the schema does not define
categories of resources and the provided core elements do not accommodate rich annotation of a resource,
such as the geographical and temporal location or resolution of a dataset that could be useful for
narrowing down its applicability. Even with the extended metadata terms [7] released by the Dublin Core
Metadata Initiative (DCMI) — an open organization supporting shared innovation in metadata design and
best practices — such an issue still exists. For example, the resource type ‘Bibliographic Resource’ in
Fig. 1 is a term in the DCMI extended terms [7], whereas the specific type ‘Figure’ is not and has to be
added by the metadata curator.

[Insert Figure 1 about here]

Other metadata standards further extend the functionality for annotating the production process of a
resource, such as the data lineage model in ISO 19115 [8] and ISO 19115-2 [9]. Two initiatives, the Proof
Markup Language (PML) [10] and the Open Provenance Model (OPM) [11], have developed enriched
categories and properties for representing and capturing provenance. Three top categories — entity,
process and agent — arise from those works. By using them one can describe a process such as the
generation of a figure through which an entity (the figure) was produced, the source entities such as
datasets and models used in the process, and agents such as people and/or organizations participated in
the process. Those categories became the core of the recent World Wide Web Consortium (W3C) PROV
Data Model (PROV-DM) [12] that was derived from those earlier efforts.

Another significant advancement in those metadata schemas and provenance models [7, 10–12] is
building on the principles of linked data, using Uniform Resource Identifiers (URIs) as identifiers of
resources, rather than literal values. For example, the third reference record in Fig. 1 may be replaced by a
URI ‘http://data.globalchange.gov/article/10.1080/01490419.2010.491031’ that points to a webpage
presenting more information about that document, such as title, document type, source journal,
publication year, and so on. The use of URI is just one of the many features that are enabled by the Semantic Web, a new generation of the World Wide Web [13]. The Semantic Web presents a Web of Data compared to the traditional Web of Documents. It adds machine-readable meanings such as more specifically defined categories and annotations to data by using ontologies — specifications of concepts and relations among them — and vocabularies — arranged terms of certain topics — encoded in the Resource Description Framework (RDF) format [14]. For instance, the webpage corresponding to the above URI is just the front end of a piece of data stored in an online database. While humans read the textual description on the webpage and know that it is about a journal article, machines can read data from the back end and recognize the resource type ‘bibo:Article’ (for meaning of the prefix ‘bibo’ see Table 1) by tracking the ontologies used in the data.

[Insert Table 1 about here]

**Linking for tracking**

The aforementioned categorization and annotation focus on the description of individual entities, processes and agents. The Semantic Web allows links to be established among those individual instances, such that in provenance tracking one can retrieve not only the literal description of a dataset used in a research but also an accessible or downloadable version of the dataset itself. In the Global Change Information System (GCIS) [15] under development through the U.S. Global Change Research Program (USGCRP), those Semantic Web technologies have been utilized to capture and present provenance information. The initial focus of GCIS is to support the third United States National Climate Assessment (NCA3). It will present the NCA3 report and also incorporate integrated access to inter-linked resources supporting that report. This significantly enhances transparency of the report, and also enhances the ability of decision-makers to understand the conclusions and to use the underlying data for their own purposes.
The inter-links among provenance information in the GCIS are realized by using properties defined in a number of ontologies, including the PROV Ontology (PROV-O) [16] — an ontology for representing and interchanging provenance information from the W3C PROV-DM. For example, Fig. 2 shows a part of the provenance information captured from the third reference in Fig. 1. Most properties in that graph are from the PROV-O. Properties from a few other domain-specific ontologies, such as the Bibliographic Ontology and the GCIS Ontology (Table 1), are also used. Those specific properties better describe a few relationships — such as those between instruments and sensors — than the general properties from the PROV-O.

[Insert Figure 2 about here]

By categorizing, annotating and linking provenance information, the finished GCIS will be capable of answering provenance-tracking questions for the final NCA3, such as (1) which datasets were used in the analysis and projection of global sea level rise or (2) which agencies and individuals are working on projects related to societal impacts of extreme weather events. The GCIS is intended to be a Web-based source of authoritative, accessible, usable and timely information about global change for use by scientists, decision-makers, and the public. The Semantic Web technology will help make the GCIS a part of the Web of Data, such that other tools and services are also able to interact with data and information in the GCIS and thus create added values in approaches that are applied to address socio-economic, physical, ecological and other intellectual challenges.

Persistent and universally resolvable identifiers such as DOI (Digital Object Identifier) are widely accepted for research articles and increasingly also for data; ResearcherID and ORCID (Open Researcher & Contributor ID) for people makes literature and data easily accessible and citable; and global change research increasingly benefits from the open-access literature and datasets [17]. We argue that the global change research community should take one step further with the curation of provenance information —
such as what is going on with the GCIS. Those works as a whole promote the meaningful eScience [18] — digital or electronic facilitation of science — and wider participation from the global change research community is desired.

Concluding thoughts

As global change information becomes both more abundant and increasingly critical, our need to know more about what, how, when, where, and why information is produced is becoming ever more necessary. Well-curated provenance information makes scientific workflows transparent and improves the credibility and trustworthiness of their outputs. It also facilitates informed and rational policy and decision-making based on the outputs of global change research. For all these reasons, the work on provenance is timely and foundational and is now an embedded component of the Global Change Information System, and a sustained approach to climate assessment.

References

http://dublincore.org/documents/dcmi-terms


http://www.w3.org/TR/prov-dm


http://www.w3.org/RDF/


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Author contributions

All authors contributed to the planning of the paper. X.M. led the work. P.F. contributed the use case-driven Semantic Web application method which generated the provenance graph in the global sea level rise use case. C.T. participated in use case analysis and provided suggestions on ontologies to be used. X.M. prepared the figures. All authors contributed to the writing of the paper.
Tables

Table 1 | A list of ontologies and schemas, their namespace prefixes and corresponding URIs

<table>
<thead>
<tr>
<th>Full name</th>
<th>Namespace prefix</th>
<th>Namespace URI</th>
</tr>
</thead>
<tbody>
<tr>
<td>The PROV Ontology</td>
<td>prov</td>
<td><a href="http://www.w3.org/ns/prov#">http://www.w3.org/ns/prov#</a></td>
</tr>
<tr>
<td>The Bibliographic Ontology</td>
<td>bibo</td>
<td><a href="http://purl.org/ontology/bibo/">http://purl.org/ontology/bibo/</a></td>
</tr>
<tr>
<td>The Dublin Core Metadata Initiative Metadata Terms</td>
<td>dct</td>
<td><a href="http://purl.org/dc/terms/">http://purl.org/dc/terms/</a></td>
</tr>
<tr>
<td>The GCIS Ontology</td>
<td>gcis</td>
<td><a href="http://data.globalchange.gov/ontology">http://data.globalchange.gov/ontology</a></td>
</tr>
<tr>
<td>The Resource Description Framework Schema</td>
<td>rdfs</td>
<td><a href="http://www.w3.org/2000/01/rdf-schema#">http://www.w3.org/2000/01/rdf-schema#</a></td>
</tr>
<tr>
<td>The eXtensible Markup Language Schema</td>
<td>xsd</td>
<td><a href="http://www.w3.org/2001/XMLSchema#">http://www.w3.org/2001/XMLSchema#</a></td>
</tr>
</tbody>
</table>
Figures

![Image of Global Sea Level Rise](image)

**Figure 1** | Collected metadata records of a figure using Dublin Core metadata terms. The global sea level rise figure on the left is from the draft report of the third National Climate Assessment in the United States. In the table on the right, the metadata element ‘References’ is from the DCMI extended terms [7], and the others are from the core elements [6].
Figure 2 | A part of the provenance information of a journal article. a, Three starting-point classes/categories in the PROV-O and the properties that relate them. b, Conceptual map of the
provenance information captured by using PROV-O and a few other ontologies. In (a) and (b) classes/categories are represented by rounded boxes, and instances are in rectangular boxes. The first term of the record in each colored rectangular box represents the class/category of the instance, and the color of that box represents the corresponding super class/category in the PROV-O. A colorless rectangular box represents a literal record or a Web address. In (b) the record in each colored rectangular box is a URI, and the common root address ‘http://data.globalchange.gov/’ is omitted from all records here to save space. The provenance information of ‘dataset/TOPEX-Poseidon’ is shown in detail and the information of ‘dataset/Jason1’ and ‘dataset/Jason2’ is omitted here. The namespace prefix of a class or property in (a) and (b) represents its source ontology, for which the details are listed in Table 1.