Harmonizing GCW Cryosphere Vocabularies with ENVO and SWEET

Towards a General Model for Semantic Harmonization

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Abstract

This paper presents the specific process we, as part of the Earth Science Information Partners (ESIP) Semantic Harmonization Cluster, used to harmonize terms from the Global Cryosphere Watch (GCW) compilation of cryospheric terms with the Semantic Web for Earth and Environmental Terminology (SWEET) and the Environment Ontology (ENVO). In addition, we summarize a number of leading practices which may be applied to other projects/domains as well as suggest a generalized process for doing so. This paper describes the history of the effort, the technical and decision-making processes used to resolve differences between semantic resources, and describes a number of the issues encountered, with a focus on those that were addressed during the effort. Lessons learned, examples of the problems encountered and a summary of resulting leading practices growing out of this work is provided as an aid to semantic harmonization efforts in other domains by other groups.

Keywords:

Semantics, Semantic Harmonization, Lessons Learned, FAIR data, Leading Practices

Introduction

Over the last several decades it has become increasingly apparent that to solve any of humanity's pressing issues, inter- and trans-disciplinary research is needed. This requires that data that are collected, developed and described for one community become accessible and understandable by other communities; that the data become globally FAIR (Findable, Accessible, Interoperable, Reusable) (Wilkinson et al, 2016).

What is often not understood by researchers is that for data to be FAIR, it requires that both the data and its metadata be understandable by both humans and computers (FAIR Principles, 2015). This implies that semantic resources with resolvable globally unique and persistent identifiers are used in a well-defined framework that describes the structure and content of both the data and its metadata (FAIR Principle I1, 2015). Consequently, understanding and harmonizing disciplinary semantic resources with similar semantic resources in other fields is a necessary part of the agenda for creating intelligent systems across the geosciences (Gil et al, 2018) and beyond.

Historically, a substantial portion of scientific knowledge has been captured by systems based on independently developed and semantically heterogeneous semantic resources, including controlled vocabularies, glossaries, thesauri, and the termed concepts used in ontologies (see Figure 1 and section Semantic Resource Types). Typically, these resources were recorded and encoded in various ways, including spreadsheets, documents, programming languages and schemas. Consequently, the systems which were developed based on these resources, which may support large, well-established disciplinary user bases, are unlikely to naturally merge with those of other disciplines without a great deal of effort. In light of this failure, it is increasingly clear that there is a pressing need for a sound and sustainable way to align and harmonize these resources in order to allow for inter- and trans-disciplinary data discovery and use.

In this paper, we describe the methods used to harmonize cryosphere (cryo) terms from the 27 semantic resources in the Global Cryosphere Watch (GCW) with two major Earth science ontologies, ENVO and

SWEET, and propose a general process for harmonizing semantic resources across the semantic ladder. This work was done as a project through the Earth Science Information Partners (ESIP) organization.

Background

In the following subsections we describe the types of semantic resources typically used in these types of projects and the level of machine interoperability for each; provide a brief introduction to the cryosphere, the focus of this work; introduce the specific semantic resources addressed and provide a brief history of the precursor work that led to this project.

Types of semantic resources

In the Earth Sciences, broadly considered, there is no one semantic resource or semantic resource type to rule them all. In fact, the phrase *semantic resource* actually refers to a *spectrum* of artifacts ranging from simple controlled vocabularies (e.g., term list) to complex, logically rigorous structures (e.g., ontologies), each providing a level of interoperability to innumerable applications (see Figure 1). The terminology describing semantic resources can actually vary quite sharply depending on the community with which it is employed. As such, the following are types of semantic resources considered during this work along our definitions for each type.

- Controlled vocabulary (e.g., term list) - Limited set of terms in a sequential order without definition. No terms should overlap in meaning. All terms should be of equivalent granularity or specificity (Zeng, 2008).
    - Example: AGU Index of terms (American Geophysical Union, n.d.)
- Glossary - Alphabetical list of terms with definitions (Zeng, 2008)
    - Example: Glossary of Geology (Neuendorf et al, 2011)
- Taxonomy - Divisions of (preferred) terms into ordered, hierarchical groups or categories based on particular characteristics (Zeng, 2008).
    - Example: The classification of living organisms by their Kingdom, Phylum, Class, Order, Family, Genus and Species
- Data Model - An abstract model that organizes elements of data and standardizes how they relate to one another and to the properties of real-world entities (Wikipedia contributors, 2021).
    - Example: CSIRO OzSoilML_Soil Package containing classes representing notional soil units, soil profiles and soil layers (OzSoilML-Soil, n.d.)
- Thesaurus - sets of terms representing concepts and the hierarchical, equivalence, and associative relationships connecting them (Zeng, 2008).
    - Example: The USGS Thesaurus (USGS Thesaurus, n.d.)
- Ontology - More than a taxonomy in that an ontology is a structured vocabulary in which 1) terms (classes) are related by logically consistent axioms (defined in a formal language), primarily formal subclass/superclass relations where subclasses inherit all the properties of their superclass(es) and 2) terms are associated with consistently written, human-readable definitions (such as from a controlled vocabulary) which are aligned to their logical axioms.
    - Example: ENVO (ENVO, n.d.)

Sometimes termed the semantic spectrum (McCreary, 2006), the semantic ladder illustrates the type of extent of machine-aided interoperability of semantic resources such as vocabularies, thesauri and ontologies. Each type of semantic resource defined above has been placed on the semantic ladder depicted below in Figure 1 along with the three resources used in this work (GCW glossaries, SWEET, and ENVO).

Figure 1: A depiction of the Semantic ladder loosely based on Dan McCreary's 2006 presentation (McCreary, 2006).

The cryosphere

The cryosphere is 'one of the earth's spheres of irregular form existing in the zone of interaction of the atmosphere, hydrosphere and lithosphere, distinguished by negative or zero temperature and the presence of water in the solid or supercooled state' (cryosphere, n.d.). The term refers collectively to the portions of the earth where water is in solid form, including snow and ice cover, sea ice, river ice, lake ice, glaciers, ice caps, ice sheets, seasonally frozen ground and perennially frozen ground (permafrost).

The cryosphere is an integral part of the global climate system, so monitoring it is important in studying the state of the earth's climate. It acts like a reflective shield, protecting the Earth from getting too warm because snow and ice reflect more sunlight than open water or bare ground. The presence or absence of snow and ice, therefore, affects heating and cooling over the Earth's surface, influencing the entire planet's energy balance. Changes in snow and ice cover affect air temperatures, sea levels, ocean currents, and storm patterns all over the world (Why We Study the Cryosphere, n.d.).

Given the geographic scope of the cryosphere, its data comprises several scientific and sociological disciplines, and is thus extremely heterogeneous in both type and size. A few examples include the often huge remote sensing data sets acquired by satellites, airplanes and more recently drones; long-time series data gathered at stations such as permafrost borehole temperature profiles and ship-born sea ice and ocean temperature profiles; 'in-situ' data gathered in the field such as snow depth, density and water equivalent; samples such as ice cores, sea ice or permafrost soil samples; laboratory measurements of samples and experimentally derived data; and computer-generated environmental models.

ESIP

The Earth Science Information Partners (ESIP) is a non-profit organization with the vision of being a 'leader in promoting the collection, stewardship and use of Earth science data, information and knowledge that is responsive to societal needs' (Earth Science Information Partners, n.d.). Supported by the U.S. National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), and the U.S. Geological Survey (USGS), and with more than 130 member organizations, ESIP provides a neutral, open, and welcoming space for collaboration between researchers, educators, industry, and government agencies to accomplish these goals.

In 2009, ESIP convened a Semantic Web Cluster to help its community adopt a wide range of technologies to digitally represent knowledge from diverse scientific domains and bridge it to other data and information. As the popularity and importance of semantic technologies grew, this cluster was promoted to become the Semantic Technologies Committee in 2016 to address needs in this operational space and participate in the Program Committee, the executive branch of ESIP. In ESIP, Committees are able to convene their own clusters, and as recognition of the substantial expertise and domain knowledge present within the ESIP community, several subsidiary clusters were formed to address specific aspects of semantics. One of the clusters that spun off was the ESIP Semantic Harmonization Cluster which was formed in 2018 to propose a route towards sustainably bridging terminologies for the Earth Sciences and to disseminate best practices for harmonizing semantic resources. These terminologies would need to be usable across implementation scenarios and user communities, as well as applicable across the spectrum of semantic resource types - that is, from resources with weak expressivity such as controlled vocabularies and glossaries (e.g., Figure 1), through those that support best practices for publishing structured scientific data on the Web (Shepherd et al, 2022), and to those that enable computational reasoning – i.e., ontologies.

SWEET

The Semantic Web for Earth and Environmental Terminology (SWEET) (SWEET, 2022) organizes over 11000 Earth and Environmental concepts into roughly 200 separate ontology modules based on nine top-level categories (below), some of which contain subcategories with cryosphere-related terms (Table 1):

- Representation - Math, Space, Science, Time, Data,
- Realm - Ocean, Land Surface, Terrestrial Hydrosphere, Atmosphere, Heliosphere, Cryosphere, Geosphere,
- Phenomena (macro-scale) - Ecological, Physical,
- Process (micro-scale) - Physical, Biological, Chemical, and Mathematical,
- Matter - LivingThing, MaterialThing, Chemical,
- Human Activities - Decision, Commerce, Jurisdiction, Environmental, Research,
- Property (observation) - Binary Property, Quantity, Categorical Property, Ordinal Property
- State (adjective, adverb) - Role, Biological, Physical, Space, Chemical, and
- Relation (verb) - Human, Chemical, Physical, Space, Time

Initially developed at NASA's Jet Propulsion Lab (Raskin and Pan, 2005) and originally based on the Global Change Master Directory (GCMD) keywords (Nagendra et al, 2001), SWEET is now officially under the governance of the ESIP federation. Despite the broad coverage, historically, SWEET did not include terminology definitions or their equivalent machine readable axioms, so despite routinely being referred to as a set of ontologies in relation to the semantic spectrum, in many areas SWEET is more along the lines of a taxonomy or *lightweight* ontology (Giunchiglia and Zaihrayeu, 2009). SWEET is broadly used across Earth science repositories given these historic ties to NASA's systems.

ENVO

The Environment Ontology, ENVO was initially created to represent environmental characteristics in which biological entities are found. ENVO includes, for example, descriptions of physical environments such as geological, ecological, or astronomical (Buttigieg et al, 2016, 2013). As such, expanding ENVO to include cryospheric terms enhances ENVO's coverage of physical environments.

In relation to the semantic ladder (see Figure 1), ENVO is an ontology with both human and machine-readable axiomatic definitions. It has been developed following the recommendations and principles of the Open Biological and Biomedical Ontologies (OBO) Foundry and Library (OBO Technical Working Group, 2022) and can be formally represented in OWL or OBO formats. ENVO is aligned with the Basic

Formal Ontology (Arp et al, 2015; BFO, 2019) at an *upper* level, so that ENVO is interoperable with other OBO ontologies.

The top levels of ENVO have roots that roughly branch into entities or processes. In our final classification, the term 'cryosphere' was placed under 'astronomical body part' which is under 'material entity/fiat object part'.

Compared to SWEET, ENVO has axioms and overall is a more formally developed ontology. The scope of ENVO is broader and covers descriptions of any type of environment, whereas SWEET specializes in earth system science.

Previous Work

In the following subsections, we describe the precursor projects and an event that motivated and enabled this work.

The Semantic Sea Ice Interoperability Initiative (SSIII)

R. Duerr and her collaborators had previously developed a set of sea ice ontologies (Duerr et al, 2015). These were based on the March 2014 draft (Mundial et al, 2014) that updated the original version of the World Meteorological Organization Sea Ice Nomenclature (WMO/OMM/BMO, 1970) developed under the auspices of the Joint WMO-IOC Commission for Oceanography and Marine Meteorology (JCOMM) Expert Team on Sea Ice.

Despite having used the then current best practices for making ontologies operationally available, the new sea ice ontologies were made inaccessible when the system underlying the Persistent Uniform Resource Locators (PURL), used to provide global unique location (i.e., URL) for each term within the ontologies, was transitioned from the OCLC, Inc. (OCLC, Inc., n.d.) – a nonprofit global library cooperative providing shared technology services, original research and community programs– to the Internet Archive (Internet Archive, n.d.) in 2016 just as the Google Code hosting site was retired due to the proliferation of hosting services such as GitHub, GitLab, BitBucket, etc.

Fortunately, the ontological work was not entirely lost as the editors of the Environment Ontology (ENVO) had independently discovered the Duerr sea-ice ontologies and had initiated a project at the Alfred Wegener Institute for Polar and Marine Research to explore how ENVO's axiomatization could build upon these terms. This link set the stage for closer collaboration between ENVO, an ontology within the OBO Foundry, and other ontologies more native to Earth and environmental science (see the ENVO discussion above).

GCW Nomenclature Project

The World Meteorological Organization's (WMO) Global Cryosphere Watch (GCW), 'an international mechanism for supporting all key cryospheric in-situ and remote sensing observations' (Global Cryosphere Watch, n.d.), has set the development of a cryospheric glossary as one of their goals to enable global interoperability of cryospheric data. As a first step forward, the GCW collected some 27 cryospheric glossaries, including the sea ice glossary used in the SSIII project above, containing a total of 4147 terms, of which only 2249 were unique, and commissioned R. Duerr to analyze these terms to indicate the terms:

- that are not problematic from a semantic standpoint,
- where multiple definitions could be coalesced into a single definition,
- where the terminology was inconsistent and therefore problematic from a semantic standpoint, and
- where community resolution was needed to either agree on a definition or to split the terms up into separate entities.

This analysis resulted in two reports (Duerr, 2018a, 2018b) containing tables for terms that fall into the categories above and a discussion of how these terms align with existing semantic resources such as ENVO, SWEET, the Global Change Master Directory (GCMD) keywords (GCMD, 2023), and the Climate and Forecast (CF) metadata conventions (Eaton et al., 2022). This work of R. Duerr forms the input data for the work reported in this paper.

Vocabulary Camp

Vocabulary Camps, or VoCamps, are a series of informal events where interested people get together to spend dedicated time creating lightweight vocabularies/ontologies for the Semantic Web/Web of Data (What Is VoCamp, n.d.). Over the past 15 years more than 30 VoCamp events have been held on an extremely wide variety of Earth, environment, and spatial science topics.

The initial impetus for this harmonization work stemmed from a suggestion made to co-author G. Berg-Cross at the 2017 International Association for Ontology and its Applications (IAOA) Summer Institute on Upper Ontologies (IAOA, 2017) which led him to organize a VoCamp (Berg-Cross et al, n.d.) session with 'glacier' as the topic chosen to facilitate cross-domain work with the hydrology community which was interested in including cryospheric processes in their work. The hackathon-style VoCamp was organized around an interdisciplinary and internationally distributed work group made up of domain experts, knowledge engineers, and people with related experiences scattered across Europe, North America, and the South Pacific. To facilitate discussion, domain and knowledge engineers scoped a starter list of 33 relevant Cryo terms based on the GCW assessment described above. The terms were organized into categories (e.g. process, part of a glacier, material, landforms, zones) with the goal of aligning this set of glacier-related terms around a core taxonomy and refining an initial draft conceptual model used to organize the terms. Over one day, the 14 hour hackathon was conducted to refine the conceptual model organizing these terms into glacial object types, features, composition (e.g., frozen water matter) and processes. The hackathon was successful enough for participants to seek a way to continue this work on a regular basis, which led to the formation of the ESIP 'Semantic Harmonization' cluster that same year. A new series of ESIP hackathon sessions was organized to proceed.

Methods

A series of monthly teleconferences coordinated by the ESIP Semantic Harmonization Cluster was initiated to continue the previous work described above. Figure 2 depicts the process that was used to harmonize those cryosphere resources with ENVO and SWEET.

The first task discussed was to select the ultimate set of semantic resources to harmonize. Given ESIP's recent acceptance of stewardship for SWEET, the GCW nomenclature work described above, and ENVO's interest in incorporating sea ice and other cryospheric terms, these were the targets agreed to by the cluster membership. Work proceeded by identifying SWEET terms that were cryospheric from within that subset of SWEET files whose name indicated that they were likely to contain relevant terms (see list of files addressed in Table 1). A Google sheet containing the relevant SWEET terms was created for each SWEET file addressed (rduerr, 2023).

For each term on the spreadsheets, the team determined whether there were equivalent terms in the GCW compilation. If not, the term was not addressed further. If so, the ENVO ontology was examined and compared to the GCW definitions, starting with the assumption that the placement of the term in the SWEET hierarchy was valid. Additions or updates to ENVO were made using guidelines developed by Seppälä et al (2017). This included creating minimal but robust definitions following the genus-differentia model which produces definitions of the form 'X is a Y that Zs' and numbering each discrete differentia in the definition as well as ensuring that the axioms for the term reflected the differentia in the definition (see Figure 3 for an example). Many of the terms in the GCW compilation included additional information that went well beyond a definition. These extra materials were not included as part of the ENVO definition, but instead kept as separate annotating comments on the ENVO term. When revising definitions or adding terms to ENVO, we paid special attention to the taxonomically inherited axioms of each class, correcting issues higher in the ontology hierarchy or adding additional levels to the hierarchy as needed.

Figure 2: Overview of the harmonization process used in the project and described below. It should be noted that boxes with rounded corners represent processes, while diamonds represent decisions and labeled arrows represent inputs to, triggers for or outputs from a process.

Figure 3: Term added to the ENVO ontology using a GCW derived definition with additional comments.

Initially, the examination of terms in ENVO occurred using the Protégé ontology editor (Musen, 2015) and the development branch of ENVO available from the ENVO GitHub repository. We were editing/updating ENVO one term at a time. However, later in the project, after having worked through many terms using this process, we switched to using a ROBOT spreadsheet (Jackson et al, 2019; Overton et al, 2015) to automate the process of accessing and updating ENVO in bulk. ROBOT is a command-line tool for working with ontologies, with special emphasis on Open Biomedical Ontologies (OBO). It provides convenient commands for merging ontologies, extracting subsets, filtering for selected axioms, running reasoners, and converting between file formats. Commands can be chained together to form powerful, repeatable workflows. Using ROBOT improved overall efficiency as well as decreased the conceptual workload for those team members without a great deal of ontology engineering experience, though it did not decrease the time required to assess the GCW definitions or any existing ENVO definitions and axioms.

Finally, to formally record the relation between ENVO and SWEET terms, initially, we had worked to include the new or updated ENVO definitions along with a cross-reference to the ENVO term using the `oboInOwl:hasDbXref` construct within the SWEET file using SWEET's existing GitHub repository and update process. However, after a few such updates had been made, the SWEET community determined that the long term vision for SWEET would be enhanced if it were made a hub for multiple definitions. At that point, direct updating of SWEET halted, while necessary updates to SWEET's processes were made. Instead, we used the recently developed Simple Standard for Sharing Ontological Mappings (SSSOM) (Matentzoglu et al, 2022) to document the relationships between the identified SWEET terms and their related ENVO terms.

To use SSSOM, we first populated a spreadsheet with our newly entered ENVO terms alongside potential matching terms in SWEET. For each term, we determined a potential relationship that we expressed using SKOS predicates, by analyzing the placement of the SWEET and ENVO terms in their class hierarchies, and comparing their definitions and axioms (if any). While time consuming, this human curated approach proved to be much more accurate than the more common machine learning or automated string matching approaches which generally ignore both differences in the organization of the hierarchies of different resources as well as the richness of the subclasses and axioms underlying the mapped terms (see Results section below).

In addition to the SKOS relationship between terms, such as `broadMatch` or `relatedMatch`, we recorded a comment explaining the reasoning behind the `match_type` assigned. In many cases, these comments also include suggestions for future work and/or conditions for changing the `match_type` if either ontology is updated. For example, for the term Arete we recorded the comment that 'In SWEET an arete is considered to be a type of plain, but in ENVO and actually an arete is a kind of ridge; so the SWEET hierarchy needs to be changed. It should be noted that SWEET has 3 kinds of ridge; the closest is http://sweetontology.net/realmLandOrographic/Ridge.' The SSSOM file generated was added to the ENVO repository on GitHub and the ESIP Community Ontology Repository (COR, n.d.).

Results

Of the 626 terms in the polar subset of ENVO, a total of 302 terms were added or updated as a part of this work. This represents roughly 15% of the unique terms in the Global Cryosphere Watch compilation of cryospheric terms; though it should be noted that many of the other GCW terms had been addressed in ENVO prior to this project. Of these terms, 151 terms were mapped from ENVO to SWEET using the SSSOM mapping standard. This mapping is available in the ENVO GitHub repository (Buttigieg et al, 2023).

Table 1 contains a list of the SWEET ontology files addressed during this work, the number of cryosphere terms identified in each file, the number of these that were also present in the GCW compilation and the number that were common between all three sources.

Table 1: SWEET files addressed during this work.

SWEET File	**Total Terms in SWEET File**	**Cryospheric Terms in SWEET File**	**GCW Terms Overlapping with SWEET Terms**	**GCW + ENVO Terms Overlapping with SWEET terms**
realmCryo.ttl	32	32	12	11
phenCryo.ttl	17	17	14	11
mtrWater.ttl	41	14	10	9
phenAtmoFog.ttl	32	3	3	3
realmClimateZone.ttl	24	3	3	1
realm.ttl	20	1	1	1

realmOcean.ttl	26	1	1	1
realmSoil.ttl	34	5	5	5
propTime.ttl	41	5	0	0
propSpaceThickness.ttl	32	3	3	3
phenHydro.ttl	33	2	1	1
phenAtmoPrecipitation.ttl	58	15	13	13
realmLandGlacial.ttl	18	16	11	8
phenSolid.ttl	63	7	4	3
Total Terms assessed	**471**	**124**	**81**	**70**

Of the almost 500 terms in the 12 SWEET files identified as containing some cryospheric terms, 124 or 26% of those were cryospheric terms. And, of those 124 cryosphere terms, 81 or 65% were also found in the Global Cryosphere Watch, 70 or 56% were found among all three resources. Again, this overlap of similar terms found in multiple resources and also the lack of comprehensiveness of terms relevant for a domain in any one resource shows the need and value of our work, which is to identify gaps between semantic resources and add to and align vocabularies as much as possible.

Figure 4: A partial ENVO representation of harmonized 'ice calving process' terms. Blue boxes represent terms within the ontology, the lines indicate subclass (i.e., is a) and other relationships between terms, while dotted gray boxes indicate that the enclosed terms inherit the relationships from other levels within the ontology.

Figure 4 provides a graphic representation of the results of harmonizing ENVO terms related to the 'ice calving process'. This has the advantage of showing terms and relationships that are not immediately obvious when looking at one term at a time. In ENVO, 'ice calving process' is represented as a form of (subclass of) mass wasting. The subclasses of ice calving process captured differentiae noted during our glossary review, in particular, 'where' the ice was calved, either into water or upon land, and 'from' which entity it was calved, i.e., an iceberg or glacier. The definitions of these terms often reveal semantics which are not apparent in their commonly-used labels. 'Land ice', for example, is a term used to refer to ice formed over land masses, rather than present upon them, thus allowing marine icebergs to be a valid (sub)subclass. That is, by definition, icebergs come from land ice versus ice floes which are an expanse of sea ice. So, a marine iceberg is an iceberg which is a type of land ice mass, even though it's no longer on land. Relationships between terms (i.e., axioms) come from another OBO Foundry ontology, the Relations Ontology (Huntley et al, 2014; Mungall et al, 2020), which supports reasoning and verifies logical coherence.

As mentioned earlier, SSSOM was used to document the relationship between cryospheric terms in SWEET and ENVO. In total, 151 relationships between terms were developed. As you can see from Figure 5, roughly 40% of the terms were categorized as being a `closeMatch` which typically implies that positioning within each hierarchy is comparable but that SWEET's lack of definitions and decision to allow multiple possibly divergent definitions per term inhibited assumptions of exact equivalence. An additional 40% of the terms were categorized as being related matches, which typically implies that while the terms are in some way related, that positioning within each hierarchy is sufficiently different to eliminate there being any possibility that the terms are exactly equivalent. For example, if a term was considered to be a process in ENVO and a landform in SWEET, the match was deemed a related match. The remaining 20% of the terms were either categorized as being broad or narrow matches indicating that one of the terms is less specific than the other. Broad matches provided the bulk of these types of matches indicating that the ENVO term was more specific than the SWEET term.

Figure 5: Match types in the SSSOM created for ENVO and SWEET

It is quite common in the field for folks to attempt lexical matching of ontologies (Euzenat and Shvaiko, 2013; Liu et al, 2021), that is, matching based on similarity of the un-defined concept label only. To investigate the impact that this would have had on the ontology term relationships developed here, the match types assigned to the 61 lexically equivalent strings in the SSSOM file were examined. Figure 6, provides a summary of the match types found. Roughly half of the terms matched closely; while the other half did not; indicating that a purely lexical match would be wrong in our case roughly half the time.

Figure 6: Match types for Lexically Equivalent Strings

As summarized in Figure 7, we also characterized the reasons for the match types chosen for those 61 lexically equivalent strings. While these characterizations are subjective and the number of terms addressed is small, the results are still instructive. As you might expect, most of the lexically equivalent terms rated as being close matches did not have definitions in SWEET (25 terms). However, there were 6 such terms where it also was not clear that the placement of the term in each hierarchy was equivalent. For example, SWEET considers fiords to be a type of estuary, while ENVO doesn't. Similarly, ENVO considers rime to be a type of frost; while in SWEET frost and rime are parallel concepts placed in different parts of the overall hierarchy. In addition, there were 21 terms where the type of the term in each ontology was different. For example, in SWEET, terms such as permafrost are 3-dimensional geometric objects, while in ENVO they are environmental materials. Moreover, in 9 cases, the reasons for not equating the SWEET and ENVO terms were complex, typically involving both definitional and structural differences between the two resources. In one such case, the term had been deprecated in SWEET. In another such case, SWEET had two identical terms defined in different branches of the SWEET hierarchy. In 5 cases, the existing SWEET hierarchy was deemed to be suspect. GitHub issues have been created for these cases.

Figure 7: Reasons why lexically equivalent terms were not said to be semantically equivalent

Lastly, over the last year interactions with other communities, both within ESIP and beyond, spurred us to generalize the harmonization process so that it could be tailored to the needs of other communities. Figure 8 depicts this general process using the GCW glossaries, ENVO and SWEET purely as examples of the types of resources that can be harmonized.

Figure 8: A Generalized Harmonization Workflow.

A description of Figure 8 from left to right is: 1) Existing thematic semantic resources in a variety of formats of term-definition pairs are identified by domain experts, who work together with semantic technology and ontology experts. 2) Domain experts identify source/target terms for harmonization; usually those required to advance their work. If definitions, comments, or provenance do not accompany terms, more work will be needed to understand and describe each term. Semantic technology and ontology experts work with the domain experts to reduce ambiguity by comparing terms and definitions, splitting or merging terms, and updating targets and formalizing definitions where necessary (see Discussion). 3) The resulting terms and definitions can then be encoded in one or more semantic resources (including their provenance). To allow machine-actionable search and understanding of terms, formal axioms need to be written. This is best done by a collaboration of domain experts who know the field along with semantic technology and ontology experts who know the logic and technology. The result is a domain-correct and machine-readable final set of terms described and expressed with formal axioms. If OWL is used, reasoners can be used for quality assurance and control (QA/QC) and other logical analyses. An example of a term occurring in different hierarchies in SWEET and ENVO is 'sea ice'. 4) Lastly, multiple semantic/ontology resources can be formally aligned, in our case documented with SSSOM.

Discussion

Here, we discuss issues found regarding harmonizing terminology and definitions, harmonizing across different ontology hierarchies, and finally sociotechnical issues.

Harmonizing glossaries and ontologies

As you might expect, even if involving similar if not identical topics, harmonizing semantic resources developed by different groups over different periods of time is fraught with issues. However, using analysis methods such as those promulgated by the semantics community (Seppälä, Ruttenberg, and Smith 2017) can help clarify, simplify and resolve many issues.

Broadly over the course of this project two major kinds of glossary inconsistencies were encountered; terminology incoherence and imprecise definitions. How we dealt with each is described in the following sections.

Terminology incoherence

First, we need to simply acknowledge the fact that language is fluid, in some sense alive. Terminology meaning and usage varies and drifts over time, place and community. Consequently, there may be multiple meanings for a term depending on the exact discipline or subdiscipline defining it. For example, in the permafrost community 'hummocks' are 'small lumps of soil pushed up by frost action, often found uniformly spaced in large groups'(NSIDC, n.d.); while in the sea ice community a 'hummock' is 'a hillock of broken ice that has been forced upwards by pressure' (WMO/OMM/BMO 1970). Both definitions are equally valid but specific to usage within a particular community. It would be pointless to argue about which of these is the right definition, since both clearly are 'right' and useful in their specific community. However, semantically speaking, these are two distinct terms that can each have their own unique identifier. For example, ENVO handles this by including the terms 'sea ice hummock' (`ENVO:01001537`) and 'frost-formed hummock' (`ENVO:01001538`) both under its elevated landforms branch.

Similarly, it is often the case that a term’s meaning depends either on the organization providing the definition or the region of the world from which the definition came. In either case, arguing over who is right is still pointless; simply acknowledging and understanding the differences and generating multiple terms in an ontology appropriately is sufficient. For example, there are differences in the definition of the term 'blizzard' depending on which country or continent the definition came from. Thus, in the US the Weather Service definition is not the same as that of the Australian Bureau of Meteorology. The real issue here becomes simply ensuring that there is a superclass that is neutral enough to accommodate all the needed subclasses (in this case for any differences in the definition of the term blizzard from other meteorological services around the world).

Another case that often occurs is where the definitions of a term are not parallel concepts but are completely different but still related kinds of things. For example, the term 'thermokarst' can either be a type of landform or the process that results in those kinds of landforms. In these types of cases, resolution is simple - define multiple terms accordingly! In the case of thermokarst, the ENVO ontology includes the term 'thermokarst' (`ENVO:03000085`) as 'an irregular land surface which consists of marshy hollows, hummocks, thermokarst depressions and thermokarst lakes formed from the erosion of ice-rich thawing permafrost areas' and the term 'thermokarst formation process' (`ENVO:01001498`), which is 'a process by which landforms are formed from the thawing of ice-rich permafrost or the melting of massive ground ice.' The thing to remember here is that the labels 'thermokarst' and 'thermokarst formation process' are just that - labels and as such are easily changed without impacting in any way the organization or structure of the ontology. The only reason why the label for the term `ENVO:03000085` is not something like 'thermokarst landform' is simply that it was inserted into the ontology first and the label wasn’t updated when the formation process was added to the ontology later on.

The situation when a term's meaning changes over time is more complicated. For example, when discussing snow and ice processes prior to 1980, the term 'ablation' did not include mechanical removal of either snow or ice by processes such as wind erosion, avalanches, or calving. Now it does. While semantic technologies and languages such as OWL can deal with temporal and numeric constraints, their inclusion in ontologies such as those within the OBO Foundry has not yet been standardized. Even if such usage were standardized, it isn’t clear how such a temporal constraint could be operationalized without explicitly capturing the date the term was used wherever that term was used. For example, in Natural Language applications, associating the date when a particular text, including that term, was written would be needed, and there would always be edge cases where it would be unclear which definition was used (e.g. papers written during or near 1980).

Worst yet, are cases where there are disagreements over the more general of two concepts. Here, resolution of the question really will absolutely require discussion within the various communities involved. For example, within the cryospheric community as a whole there are disagreements about whether an ice sheet is a glacier, a glacier is an ice sheet or whether these are parallel concepts (A more complex case of 'calving' is discussed in the next subsection). In these cases, the best one can do at the moment is 1) acknowledge the problem, 2) include terms as best as one may in ontologies wherever their inclusion is absolutely required and 3) include a note to the editor in the ontology about the problem and the likelihood that the term’s placement, axiomatization and inclusion in the ontology might need to change in the future.

Precise definitions and their axiomatization

While scientists are often accused of using jargon and trying to be very precise, sometimes inhumanely so, it is surprising that many of the definitions in the various disciplinary glossaries and other vocabulary resources developed are often not semantically consistent or complete. This is one reason why formal semantics calls for 1) the careful creation of definitions using analysis methods such the genus-differentia definitional form (that is, dividing terms into classes and subclasses differentiated by properties) complemented by 2) machine-actionable axiomatization which uses a logical language to formally specify the vocabulary of concepts and the relationships among them and 3) by ensuring that the human-readable definition and the corresponding machine-actionable axioms are equivalent. Doing so can both call out and/or fix problems with existing glossaries. Inconsistencies between axioms represented in OWL, for example, can be shown by theorem provers available in tools like Protege. Using such tools helps ensure that the human readable definitions and their machine-actionable counterparts actually are equivalent, so that any machine made logical inferences are as expected by humans.

For example, let's look at the term 'calving'; which is an ablative process where chunks of ice fall off a parent body (e.g., a calving glacier). There is ambiguity in the existing dozen definitions in the GCW compilation for both the process and the resulting chunks of ice. Some definitions assume that the calving process can only happen going into water while others allow calving on land. Also some definitions allow calving to occur from any form of ice of land origin (e.g., ice sheets, ice caps, ice shelves), while others restrict it to glaciers or some other subset of all of the types of ice of land origin. What ice calved onto land would be called is not obvious, especially since the only definition of calved ice in the GCW compilation excludes ice falling onto land. To resolve the ambiguity with process terminology, we defined four subclasses in ENVO under the class 'ice calving process': calving of ice from an iceberg, calving of ice into water, calving of ice onto land (i.e., dry calving or terrestrial calving), and glacial ice calving process. Of the four subprocesses, two talk about whether the calved ice is falling into water or onto land; while the remaining two discuss where the calved ice came from - either an iceberg or a glacier. While it is unlikely that there will ever be a need for other terms for what ice is falling onto (can ice fall onto or into anything other than water or land?); there may well be the need to add terms for other sources of the falling ice (e.g. ice sheet, ice cap, thick permafrost embedded in an eroding cliff, etc.) in the future, provided of course that there are use cases where such distinctions are important.

As an example of the genus-differentia definitional form, the definition of the newly added term 'calving of ice into water' is 'An ice calving process during which a mass of ice falls from a larger mass into a body of water' where 'ice calving process' is the parent class and the rest of the sentence describes how this term is different from its parent. Sometimes you will see this form presented as 'Y is an X that Z's.' In terms of the machine-actionable axiomatization of the term, the only difference in axiomatization of the term and its parent is the addition of a water body as a participant in the process.

Another example of axiomatization of a term entered into ENVO is 'permafrost'. We created formally defined axioms that specify that 'permafrost' is a type of '`environmental material`' which '`has quality some decreased temperature`' and is '`composed primarily of some (sediment or soil or rock)`'. One of its sub-types is '`ice-bearing permafrost`' which '`has part some water ice`'. Permafrost also has a human-readable definition of 'Soil or rock and included ice or organic material at or below the freezing point of water (0 degrees Celsius or 32 degrees

Fahrenheit) for two or more years'. This is a case where the human readable definition is more precise than the axiomatization. Clearly, when or if the larger semantic community promulgates a standard way of including numeric constraints into axioms, these axioms will need to be updated, perhaps as 'has quality some 'freezing years' >=2; where 'freezing years' axioms are something like 'has quality maximum temperature < 0C' and 'has quality minimum duration.'

Mapping across inconsistent ontology hierarchies

Given the issues with harmonizing terms in glossaries as discussed above, and the vast number of glossaries, it would be shocking if two ontologies created by different groups, for different purposes at possibly different times had internal hierarchies that were the same. Yet, that doesn't mean that it is impossible to harmonize across such resources; it is just not as straightforward as simply mapping lexically equivalent terms.

Consequently, when adding terms to an existing ontology the resulting contextual structure/hierarchy for the added terms may not necessarily be the same as would occur if adding to a different ontology or if creating a new and independent ontology, say a stand-alone cryosphere ontology. But, even when creating a new ontology, the order of adding classes can result in a functionally similar but different ontology structure. That is, which terms to add first can influence where later terms are placed. So, as we added cryosphere terms one by one to ENVO, the terms were subclassed into the most relevant existing classes. This scattered some terms that, on later inspection, could have been more closely related, and the initial result may eventually be slightly changed. The piecemeal process of adding terms and creating a new whole that makes sense is difficult regardless of creating a new ontology or adding to an existing ontology and is probably non-deterministic regarding the exact same hierarchical result. Accuracy can be retained, however. A few examples follow.

For example, the concept 'greenhouse gas' encompasses both a role and a material entity. In ENVO there is no material entity that is a 'greenhouse' gas, but certain gasses can bear this role. So in ENVO, 'greenhouse gas' is a term from the Chemical Entities of Biological Interest (ChEBI) ontology (i.e., `CHEBI_76413`)' and not a term under 'gas molecular entity'. However, in SWEET, 'greenhouse gas' is a subclass of 'chemical substance' and also a subclass of 'chemical'. Apparently, SWEET does not have a role concept.

As another example, in the ENVO ontology, 'cryosol' is a subclass of frozen soil, and 'part_of' is its relationship to 'permafrost'; but in SWEET 'cryosol' is a 'categorical property', specifically a subclass of 'soil order'. Also, in SWEET, 'gelisol' is listed as a sibling of 'cryosol', whereas 'gelisol' is a synonym of 'cryosol' in ENVO.

'Snowpack' is a multi-deep subclass under 'spatial measure' in SWEET, although immediately under 'snow cover'. In ENVO, 'snowpack' is under 'snow mass', which is under 'mass of compounded environmental materials'. Given that SWEET considers the term to be a thickness and ENVO currently considers it a mass of snow, there is a mismatch. The definition in ENVO does refer to size, however, as in being large enough and persisting long enough to form layers under its own weight. Overall, the GCW analysis found eight definitions of snowpack over multiple glossaries, with many commonalities but also disagreements.

In ENVO, 'proglacial' (`ENVO:01001853`) is a 'positional quality which inheres in a bearer by virtue of the bearer in being in physical contact with , or close to, a glacial margin'. But, in SWEET, 'proglacial' is not a concept that refers to being, say, in front of a glacier, but instead is a process, i.e., found under 'glacial process' along with other processes such as 'accumulation', 'calving', and 'glacial retreat'.

In summary, the definitions and uses of terms can vary across ontologies such that hierarchies and conceptualizations differ. This makes alignment or harmonization imprecise. Delving into these differences, however, can expand one's knowledge across disciplines and perspectives and may help the expert community reassess and standardize its definitions.

Sociotechnical issues

In addition to issues related to the often ambiguous or incomplete definitions, difficulties with inconsistent ontology structures and current limitations in axiomatization, we encountered several issues that were more on the social side of the sociotechnical spectrum that needed to be resolved. These are described in the following paragraphs.

First, many GCW terms are entirely missing from either ENVO or SWEET or both. Simply put, the GCW provides a much more comprehensive compilation of terms in use within this discipline. The question then becomes one of scoping - how much coverage of the terms in the GCW would be appropriate for this work? We decided to limit ourselves to terms that were present in SWEET or ENVO and to add related terms to ENVO as were judged relevant to the existing ENVO community. For example, a number of compaction and erosion related terms were added to ENVO because material transformation processes having inputs and outputs are an important branch of the ENVO ontology. This decision constrained the work to the limited bandwidth available within the ESIP harmonization cluster membership.

Second, this work reflects the understanding that practical and resource limitations mean that collaborative development of a single encompassing semantic resource for a domain is likely to be impossible. A better target is harmonizing semantic resources within a defined scope of work, the scope of work that participants in the harmonization process care about. This can start at the lower end of the semantic spectrum by harvesting well-established and well defined terminologies as was done in this work. Agreement on the meaning of termed concepts is a first step toward alignment across the semantic spectrum and its impact on the overall ontological structure can be judged as work continues. A degree of interoperability, though minimal, is the reward.

In practice, what this also means is that it is likely that semantic modeling of any term in any ontology will only be as deep as is necessary to satisfy current use cases. For example, the term 'snow water equivalent' describes the output of a method used to determine how much water is present in a given volume of snow. Snow covering a defined area is collected and then melted. The depth of the resulting snowmelt is measured after it has been transferred to a standardized container. A value for snow water equivalent (SWE) can also be inferred via remote sensing technologies. Complete semantic modeling of this term would require that the processes of identifying, collecting, and melting a volume of snow and subsequently measuring the volume of the resulting water be modeled for ground-based methods and the algorithms used to infer SWE from remote sensing observations also be modeled. Neither SWEET nor ENVO currently model this term or many comparable terms to that level of detail; though either could be updated to include deeper modeling if and when new use cases surfaced that require it.

In general, semantic resources of any type are living objects, subject to change over time, just as all languages in use (i.e., living languages) change over time. Both ENVO and SWEET have existed for more than a decade and some of the glossaries compiled by the GCW are well over 60 years old. What this meant in practical terms was that we needed to review the history of each term and its placement within the ENVO and SWEET hierarchies for every term addressed. In some cases this meant we needed to change an ontology to use better and more recently defined terms. For example, we switched to using the Chemical Entities of Biological Interest Ontology term for water, "`CHEBI:water`", rather than the original ENVO term for water to handle issues of the hydrological precipitation process that arose when revising '`hailfall`' and '`snowfall`' in a systematic way.

As a corollary to these last several issues and given the hierarchy inconsistencies evident in comparing ontologies such as ENVO and SWEET, it should be noted that the need for semantic harmonization will only grow as long as people continue to reinvent the wheel each and every time they need to use semantic resources within their work. Similar to the old saw about standards (see image N below), currently the norm within the Earth and environmental sciences is for folks who need to use semantics to invent their own semantic resources no matter how many resources either partially or totally covering that topic already exist. A better use of these people's time would be for them to collaborate with the communities currently maintaining existing semantic resources and determining what extensions, refactoring, etc. of those resources are needed and contributing their efforts to the larger community. Having a well-maintained repository and ontology/term discovery resource for the Earth Sciences, akin to the OBO Foundry and BioPortal resources in the Biomedical community, might go a long way to helping resolve this problem which is currently inhibiting uptake of semantics in our field.

Figure 9: xkcd.com, *How Standards Proliferate* (Standards, n.d.)

Lessons Learned and Recommendations

Many lessons were learned along the way, with some noted as part of the previous discussion. The following are some of the main lessons along with recommendations for managing semantic harmonization.

Proper scope and interdisciplinary teams are needed

From a project perspective, starting with the right scope and an adequate, interdisciplinary team is important. Selecting a proper set of terms is important as is the value of building a coalition of interested parties around the selected set of concepts to harmonize. This starts with clearly identifying the conceptual space you are trying to describe and define. With the help of definitions one can analyze the conceptual space to understand the key concepts and relationships that are contained in a core subset of the terms looked at. Next is to evaluate the feasibility of a preliminary scope based on factors such as available resources and time constraints and prioritize a final set of semantic resources that need to be included in the scope based on the targeted conceptual space, stakeholders' needs, domain analysis, and feasibility considerations. It is also important to identify the stakeholders who will likely use the harmonized vocabulary and ensure that the team has a good balance of domain and semantic technology experts with good communication skills for effective collaboration and resolving any conflicts that may arise.

Glossary harmonization is foundational

Merging and splitting of glossary terms at lower levels of the semantic ladder (as well as identification of sub meanings) is needed before the more difficult alignment at higher levels of the semantic ladder because many terms can have a variety of synonyms and closely related terms that make them similar. For example, the term 'tabular iceberg' can be found in glossaries under the synonyms 'tabular berg' and 'table iceberg', and it was formerly called a 'barrier iceberg'. Similarly, ensuring that the same label is not re-used for another term within an ontology is important for minimizing confusion. This problem can be easily prevented simply by adding disambiguating phrases to the term. For example 'thermokarst landscape' and 'thermokarst process'. Once mapped, the alignment of textual definitions with axiomized representations in ontologies can be performed. For all these reasons and to make the sequence of changes to the Ontology clear (i.e., its provenance) there should be an item by item commit to updates and documentation of the changes made.

Use tools whenever possible

The well documented ROBOT Templates (Jackson et al, 2019) and their supporting scripts allow shared best practices with spreadsheet-like editing modality for more inclusivity. These tools help cross the domain expert to ontologist divide by allowing routine, asynchronous work within domain communities without relying on a trained ontology engineer.

Human expertise is important

A central lesson is that while automation, such as simple label matching and tools like ROBOT can help with routine tasks, a human-in-the-loop for things like ontology curation was needed. While time consuming, this human curated approach proved to be much more accurate than the more common machine learning or automated string matching approaches which generally ignore both differences in the organization of the hierarchies of different resources as well as the richness of the subclasses and axioms underlying the mapped terms.

As seen in the Discussion Section, there were many lessons learned in assigning the type of SKOS match between terms, especially when there is not an adequate definition in one of the ontologies. The most important of which is that when alternate definitions exist from different points of view, arguing over who is right is less useful than simply acknowledging, understanding and, following analysis, documenting the differences by appropriately generating multiple terms in an ontology.

Future Work

Based on the results of this work, the ESIP semantic community expects to continue working in three areas: 1) pushing the greater OBO Foundry and general semantics community to formalize the handling of numeric values and ranges in ontologies; 2) evolving the SWEET ontology in support of harmonization and 3) pursuing related semantic harmonization work in a number of other ESIP clusters. These topics are described in more detail in the following paragraphs.

Formalizing the handling of numeric values and ranges in ontologies

As has been mentioned previously it is often the case in science that the definition of a concept will include numeric values. For example, the composite definition for the term 'ice pellet' from the 27 glossaries in the GCW compilation and included in the ENVO ontology is 'An ice mass which is 1) transparent or translucent, 2) rounded, spherically, or cylindrically shaped, and 3) less than 5 millimeters in diameter.' Similarly, nearly all of the terms in the WMO Sea Ice Nomenclature (WMO 1970) include numeric criteria related to the age of the ice, the size of the floe, etc. Currently, there is no agreement as to a uniform way of adding numeric values, with units, as an axiom. This is critical if ontologies are to be useful for characterizing and understanding scientific data. In particular, for this project it would have been very useful if the OBO Foundry consortium had agreed to a convention for this, since, as is, many terms within ENVO currently have incomplete axiomatization where the human readable definition is more accurate and complete than the computer understandable axiomatization.

SWEET

The SWEET ontology suite is a long standing community resource and continues to evolve. Pursuant to the work described here, the harmonized GCW definitions now in ENVO are also being added to SWEET. As such, SWEET developers and the broader community of practice will soon be able to utilize SSSOM mappings to cross-reference back to ENVO and/or add further definition annotations which include the provenance available from that resource.

In addition to the SSSOM mappings, updates to the curation process, creation and enhancement of domain and observational concepts and properties, as well as the underlying technology stack supporting the resource, it was determined by the community that SWEET could fill a current gap by housing textual concept definitions from disparate Earth and Environmental science resources, thus making SWEET a *hub* for domain relevant concepts including, potentially, multiple independently sourced definitions which are not semantically equivalent. In this context, resources could be established vocabularies – e.g., GCMD, USGS thesauri, etc., – as well as resources which currently exist in an static, unstructured format – e.g., Dictionary of Geologic Terms (Bates and Jackson, 1984) or Glossary of Geology (Neuendorf et al, 2011) currently available in hard copy format, or other resources perhaps only available as a PDF. Each candidate definition is to be added using annotation properties (i.e., it will not affect any axioms in the initial investigation) with proper citation and contributor information (i.e., creator and reviewer) attached to each recorded textual definition.

It is the hope that using SWEET as hub for concept definitions will highlight similarities and gaps in Earth science conceptual descriptions and knowledge as well as provide the groundwork for making concepts more precise and increasing their expressivity. This latter point will be crucial for the future development of the resource.

Future harmonization work

We believe that semantic harmonization is an important and often missing ingredient to help find, make sense of, and usefully employ digital data as well as being critical to making data FAIR. Our outcomes and progress with the cryosphere have motivated us to begin work with other ESIP clusters in harmonizing key terminological resources in the following domains.

Table 2. Future harmonization work by Earth and Environmental science domain.

Domain	Description	Work Done To Date
Wildfires	Initial topic under the ESIP Disaster Lifecycle Cluster	Initial vocabulary (boundary, fuels, water sources, causes, wildfire behavior etc.) terms were identified from expert narratives and a conceptual model drafted from a work session.
Soils	Work in the Soil ontology and Informatics Cluster	Source glossaries identified. Topics include: ● Geolocation: surface location, sample time, depth of sample ● Soil organic carbon: bulk density, coarse fraction, organic fraction ● Metals, salts, and acids: pH, elemental analysis, and ionic exchange ● Nutrients: phosphorus and nitrogen ● Gas flux: field respiration and incubation ● Fractions: texture (sand/slit/clay) and sample subsetting (physicochemical fractionation) ● Isotopes: Radiocarbon and other isotopes
Coastal and Marine Ecological Classification Standard (CMECS)	Attempt to extend existing harmonization with ENVO	● Assess domains where CMECS and ENVO can contribute additional terms to each other ● Harmonize like terms in ENVO and CMECS
Heliophysics	Long term goal is to create a knowledge commons for heliophysics and Earth sciences	Several sessions have been held at ESIP meetings. Initial target glossaries and terms have been identified and are being loaded into YAMZ.net. A workshop to kick off the glossary harmonization effort is being planned.
Earth and Environmental science domains	Adding definitions from other semantic resources (electronic and hardcopy) to SWEET	Match candidates from GCMD, USGS Thesaurus, USGS Lithology terms, CMECS, MPD, and GEMET are currently under review. Several others are scheduled for review.

Conclusion

Alignment and semantic harmonization across the growing types of semantic resources is important for data interoperability and reuse. In this work we have shown how a focused interdisciplinary team of domain experts and semantic technology developers can effectively harmonize semantic resources using a standard method. The process developed is to review and synthesize content in a stepwise fashion from a collection of thematic glossaries into a harmonized collection and then to align these and further document them along with richer, more machine-actionable resources higher on the semantic ladder (i.e., here, SWEET and ENVO).

In piloting this process we encountered a number of issues and documented the lessons learned from these experiences. This includes many examples that we hope will help other communities attempting to perform similar activities.

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Competing Interests

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