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# 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 used by members of the of the Earth Science Information Partners (ESIP) Semantic Harmonization Cluster, to harmonize cryospheric terms gathered by the Global Cryosphere Watch (GCW) with two leading semantic resources used in the Earth and Environmental science communities - the Semantic Web for Earth and Environmental Terminology (SWEET) and the Environment Ontology (ENVO). This process led to updates to both ENVO and SWEET as well as the development of an alignment file relating cryospheric terms in ENVO to those in SWEET. In addition, we summarize a number of leading practices which may be applied to other projects/realms within Earth and Environmental science and perhaps beyond, 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.

## Keywords:

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

## Introduction

Over the last decades it has become 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 readily 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, both the data and its metadata must be amenable to reasoning by both humans and computers (FAIR Principles, 2015). This implies that formally defined language be used to describe the structure and content of both the data and its metadata (FAIR Principle I1, 2015). *Consequently, understanding and harmonizing disciplinary semantic resources with those in other fields is necessary (Gil et al, 2018).*

Historically, the data systems used by the research community were independently developed and customized to suit their requirements. Underpinning these systems are a variety of semantically heterogeneous resources, including controlled vocabularies, glossaries, thesauri and ontologies (see Figure 1 and section Types of Semantic Resources). Moreover, these underlying resources come in a wide variety of formats, including spreadsheets, documents, programming languages and schemas which are typically embedded with a non-trivial amount of tacit domain knowledge. Consequently, these data systems, which may support large, well-established user communities such as those of the Global Cryosphere Watch, are unlikely to naturally merge with those of other disciplines without a great deal of effort. *In light of this problem, it is increasingly clear there is a pressing need for a sound and sustainable way to align and harmonize these underlying semantic resources in order to allow for inter-, cross- and trans-disciplinary data discovery and use.*

The Global Cryosphere Watch (GCW) supports many historical, or legacy, discipline specific research data. The term cryosphere 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 and perennially frozen ground (permafrost). Given the geographic scope of the cryosphere, its data comprises several scientific and sociological disciplines, and is thus extremely heterogeneous. A few examples include remotely-sensed data acquired by satellites, airplanes and drones; long-term time-series data gathered at stations such as permafrost borehole temperature profiles and ship-born sea ice and ocean temperature profiles; 'in-situ' sample data such as snow depth, density and water equivalent, ice cores, sea ice or permafrost soil samples; laboratory measurements and experimentally derived data; and computer-generated environmental models.

The cryosphere is an integral part of the global climate system. The presence or absence of snow and ice, affects heating and cooling over the Earth's surface, influencing the entire planet's energy balance. Indeed, as the 2023 Global Tipping Points Report (Lenton et al, 2023) notes, of the five major systems currently at risk of crossing tipping points, four of them - the Greenland and West Antarctic ice sheets, the North Atlantic Subpolar Gyre circulation and permafrost regions all have cryospheric components. *Thus, harmonizing the semantic resources underlying the data systems holding cryospheric data is critical to enabling the inter-, cross- and trans-disciplinary research needed to understand the impacts of and to mitigate climate change.*

The Earth Science Information Partners (ESIP) is a non-profit organization with a mission to “empower innovative use and stewardship of Earth Science data to solve our planet’s greatest challenges” (Home - Earth Science Information Partners (ESIP), 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 between them. 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. 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 across the Earth Sciences to other domains, as well as to disseminate best practices for harmonizing semantic resources.* Successful bridges 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.

In this paper, we describe the methods used to harmonize cryosphere terms from the 27 semantic resources in the Global Cryosphere Watch (GCW) glossary compilation 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 ESIP *to fulfill the mandate of the ESIP Semantic Harmonization Cluster*.

## Background - Types of semantic resources

In the Earth Sciences there is no one semantic resource or semantic resource type to rule them all. The phrase *semantic resource* typically 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 varies significantly depending on the community with which it is employed. As such, the following are the types of semantic resources considered during this work along with our definitions for each.

- Controlled vocabulary (e.g., term list) - Limited set of terms in a sequential order without definition (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)
- Thesaurus - sets of terms representing concepts and the relationships connecting them (Zeng, 2008).
  - Example: The USGS Thesaurus (USGS Thesaurus, n.d.)
- Taxonomy - Divisions of 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
- 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.)

Each type of semantic resource defined above has been placed on the semantic ladder depicted in Figure 1 along with the three resources used in this work (GCW glossaries, SWEET, and ENVO).

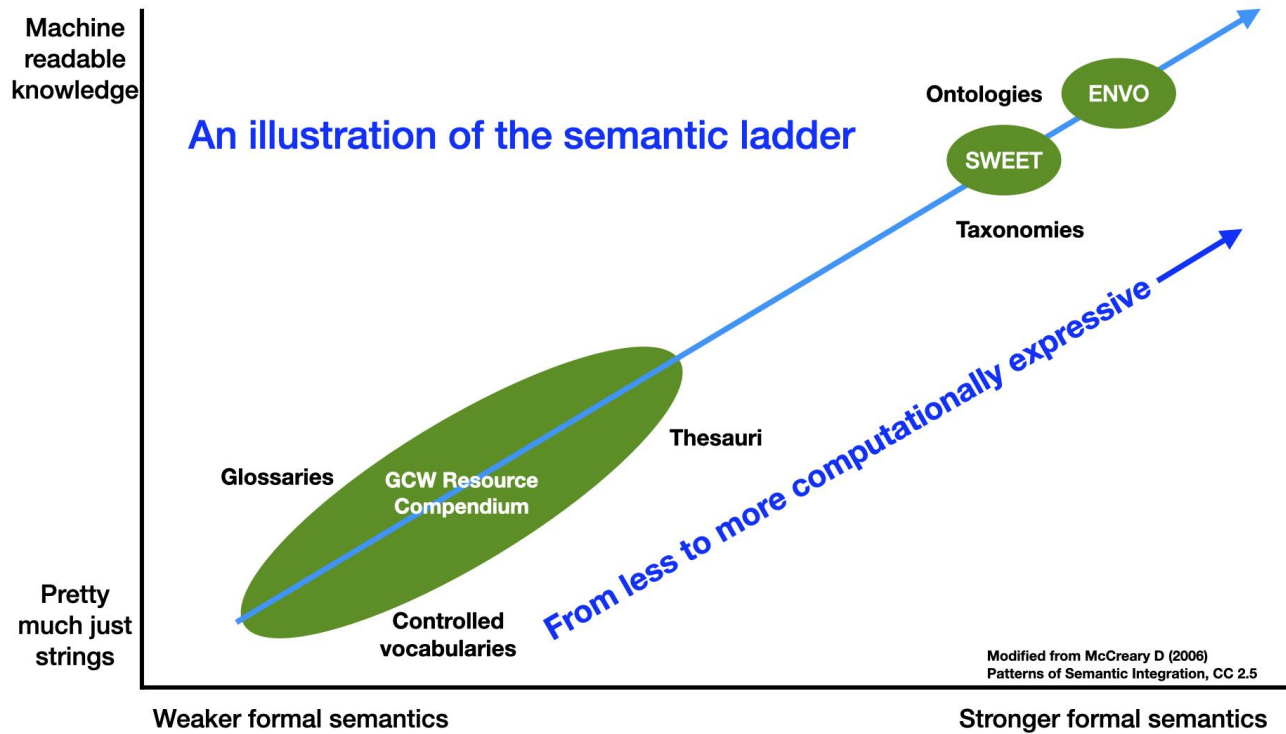


Figure 1: A depiction of the Semantic ladder illustrating the extent of machine-aided interoperability of semantic resources, loosely based on Dan McCreary’s 2006 presentation (McCreary, 2006).

## Methods

As previously described, the ESIP Semantic Harmonization Cluster was formed to develop processes for sustainably bridging terminologies across the Earth Sciences and to other related domains, as well as to disseminate best practices for harmonizing semantic resources. Figure 2 depicts the general process used here, which we think could be reused for other projects and disciplines.

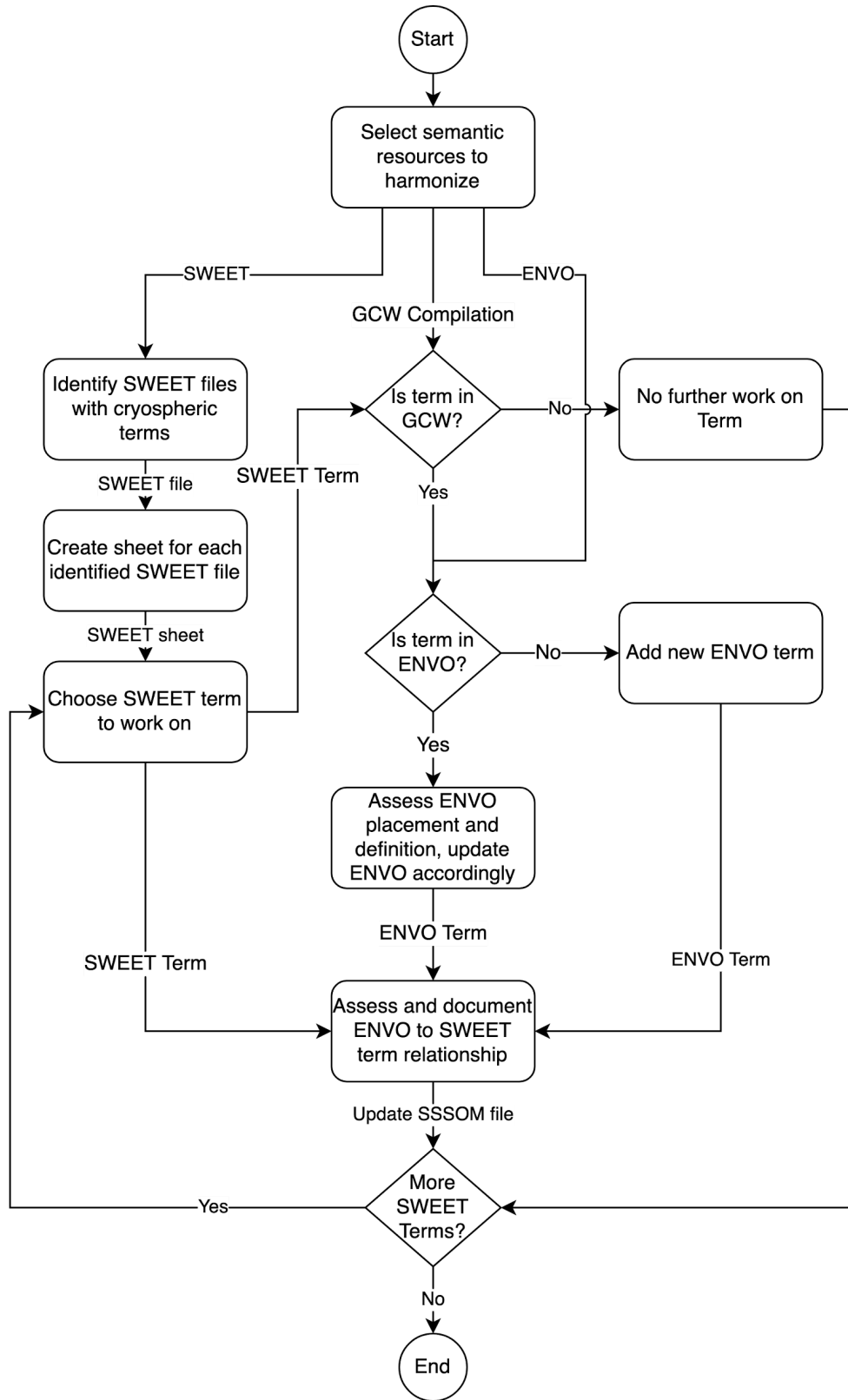


Figure 2: Overview of the harmonization process used in the project and described below.

## Step 1: Find and compile existing resources

The first task was to select the set of semantic resources to harmonize and the discipline to cover. Given the expertise within the group and the critical importance of the cryosphere to climate change impacts, we agreed that cryospheric terminology would be our focus.

This task was greatly aided by previous work commissioned by the World Meteorological Organization's (WMO) Global Cryosphere Watch (GCW) to analyze the 27 cryospheric semantic resources they had gathered (Duerr, 2018a, 2018b). One result of that work are tables containing 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.

Terms from the categories above formed the initial scope of this project.

A recent survey had identified both the Semantic Web for Earth and Environmental Terminology (SWEET) and the Environment Ontology (ENVO) as amongst the five most important semantic resources within the community (Whitehead, 2022). Of the other three resources in the group, neither QUDT (FAIRsharing Team, 2015) nor SOSA/SSN (Haller et al, 2019; Janowicz et al, 2019) contain cryospheric terminology. The last member, the NERC Vocabularies (British Oceanographic Data Centre, 2023), is focused on marine science not the cryosphere. Moreover, Wolodkin, Welland, and Grieb explicitly mention the need to bridge between SWEET and ENVO in order to facilitate reuse of biodiversity data (Wolodkin et al, 2023). The previously mentioned survey also noted that SWEET should be harmonized with other semantic resources. Consequently, the cluster agreed to harmonize GCW terminology within and between both SWEET and ENVO.

SWEET (McGibney et al, 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).

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 is being 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 the Ontology Web Language (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. Compared to SWEET, ENVO has numerous defining axioms and overall is a more formally developed ontology.

## Step 2: Semantic Harmonization

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 the list of files addressed in Table 1). A Google sheet containing the relevant SWEET terms was created for each SWEET file addressed (Semantic Harmonization Cluster, 2023).

For each SWEET 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 the SWEET term was found in the GCW compilation, then we searched for the term in the ENVO ontology. If found, we paid attention to which hierarchy, i.e., superclass, it was under compared to SWEET's hierarchies to be sure we had a match. Then additions or updates to ENVO were made using guidelines developed by Seppälä et al (2017) and extended for ENVO (Buttigieg, 2021). 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).



The screenshot shows a web browser window with the URL `http://purl.obolibrary.org/obo/ENVO_03000139`. The browser tabs include 'Annotations', 'Usage', 'OWLViz', and 'OntoGraf'. The main content area is divided into two sections:

- Annotations: 'ice fog'**: This section contains two annotations:
  - `rdfs:label` [language: en] with the value `ice fog`.
  - `definition` [language: en] with the value `Fog which is composed of particles of ice.` Below this is a `database_cross_reference` pointing to `https://orcid.org/0000-0003-4808-4736`.
- Description: 'ice fog'**: This section shows the class hierarchy:
  - Equivalent To**: No terms listed.
  - SubClass Of**:
    - 'composed primarily of' some 'water ice'
    - fog
  - General class axioms**: No axioms listed.

Figure 3: Term added to the ENVO ontology using a GCW derived definition showing parallel definition and axioms.

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 (see figure 4 for an example). 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.

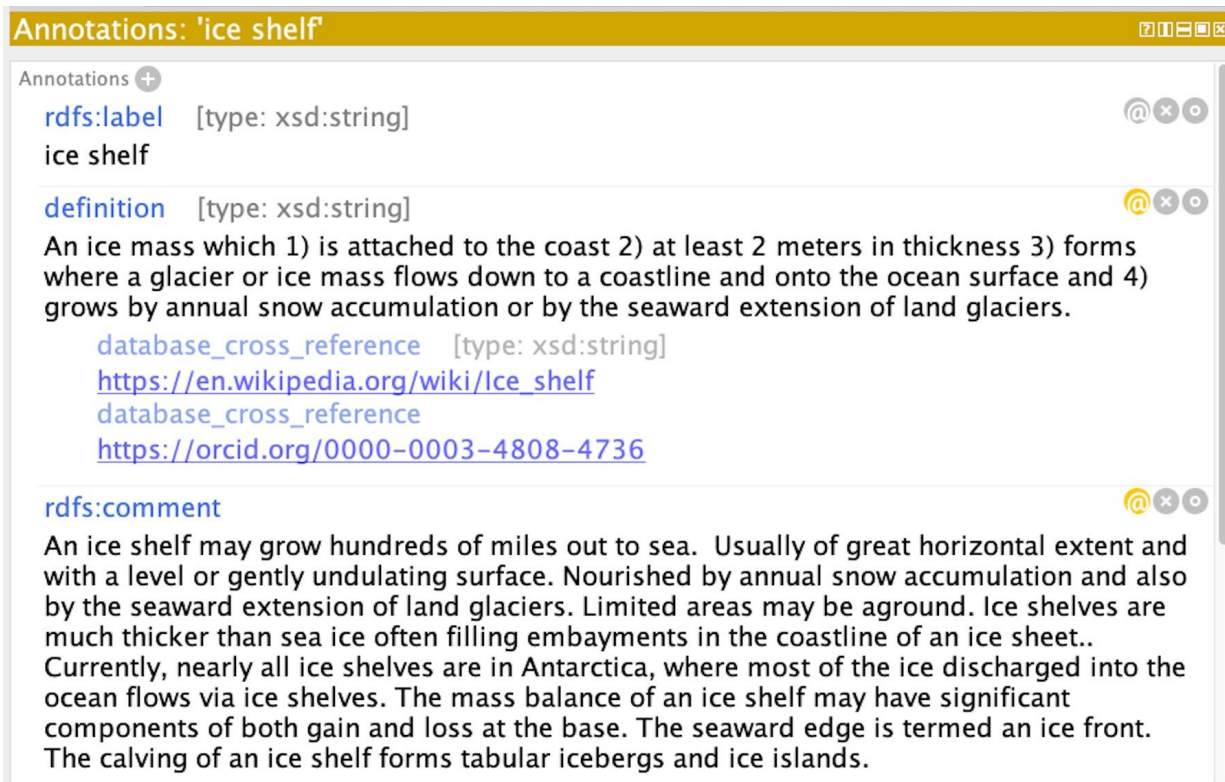


Figure 4: Term added to ENVO with numbered differentia and added GCW comments

We initially intended to update SWEET directly as well - adding definitions and relationships to the equivalent terms from ENVO directly into SWEET. However, during the project a SWEET roadmap was debated within the larger ESIP Semantic Technologies Committee which might have invalidated our work. Instead, we opted to create GitHub issues for issues with the SWEET hierarchy, to defer the addition of definitions to after completion of the roadmap, and to record SWEET and ENVO term relationships using the recently developed Simple Standard for Sharing Ontological Mappings (SSSOM) (Matentzoglou et al, 2022) (see Step 4 below).

### Step 3: Encode in Ontologies (OWL)

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 updating ENVO in bulk.

ROBOT is a general purpose command-line tool for working with ontologies and is used by many projects contributing to the OBO Foundry. It provides commands for merging ontologies, extracting subsets, filtering for selected axioms, running reasoners, and converting between file formats. ROBOT commands can be chained together to form powerful, repeatable workflows.

In this work, we created the ENVO ROBOT template and merge workflow, which allowed us to update existing as well as to add new terms to ENVO. The workflow enables the use of collaborative spreadsheets to add information into ENVO. A generalized version of the workflow is available from the ENVO wiki (Blumberg and Duerr, 2022) involving the following steps:

1. Create a GitHub issue detailing the material to be added.
2. Making a copy of the template spreadsheet formatted with headers necessary to compile a ROBOT template.
3. Preparing new terminology by filling out the spreadsheet following the best practices documented (Blumberg et al, 2021).
4. Compiling the ROBOT template spreadsheet into OWL code.
5. Use a GitHub pull request to merge the OWL code into the main ENVO codebase.

The spreadsheets we created while using the new workflow for this material added to ENVO discussed in this paper are available from our GitHub site (Duerr, 2023). Once finalized, the new information added to ENVO through the ROBOT template and merge workflow was made publicly available within a new release of ENVO using the standard ENVO release process.

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.

## Step 4: Technical Harmonization

Finally, to formally record the relation between ENVO and SWEET terms, we used the recently developed Simple Standard for Sharing Ontological Mappings (SSSOM) (Matentzoglou 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 Simple Knowledge Organization System (SKOS) predicates (Miles and Bechhofer, 2009), 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 other 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 `skos:broadMatch` or `skos:relatedMatch`, we recorded a comment explaining the reasoning behind the type of match assigned. In many cases, these comments also include suggestions for future work and/or conditions for changing the type of match if either ontology is updated. For example, for the term *Arete* we recorded a comment to the effect that in SWEET an arete is a type of plain, but in ENVO an arete is a kind of ridge; so the SWEET hierarchy needs to be changed. The SSSOM file generated was added to the ENVO repository on GitHub and the ESIP Community Ontology Repository (ESIPFed, 2023).

## Results

Of the 626 terms currently 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; 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 were mapped from ENVO to SWEET using the SSSOM mapping standard; mapping 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
<a href="#">realmCryo.ttl</a>	32	32	12	11
<a href="#">phenCryo.ttl</a>	17	17	14	11
<a href="#">mtrWater.ttl</a>	41	14	10	9
<a href="#">phenAtmoFog.ttl</a>	32	3	3	3
<a href="#">realmClimateZone.ttl</a>	24	3	3	1
<a href="#">realm.ttl</a>	20	1	1	1
<a href="#">realmOcean.ttl</a>	26	1	1	1
<a href="#">realmSoil.ttl</a>	34	5	5	5
<a href="#">propTime.ttl</a>	41	5	0	0
<a href="#">propSpaceThickness.ttl</a>	32	3	3	3
<a href="#">phenHydro.ttl</a>	33	2	1	1
<a href="#">phenAtmoPrecipitation.ttl</a>	58	15	13	13
<a href="#">realmLandGlacial.ttl</a>	18	16	11	8
<a href="#">phenSolid.ttl</a>	63	7	4	3
<b>Total Terms assessed</b>	<b>471</b>	<b>124</b>	<b>81</b>	<b>70</b>

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, and 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.

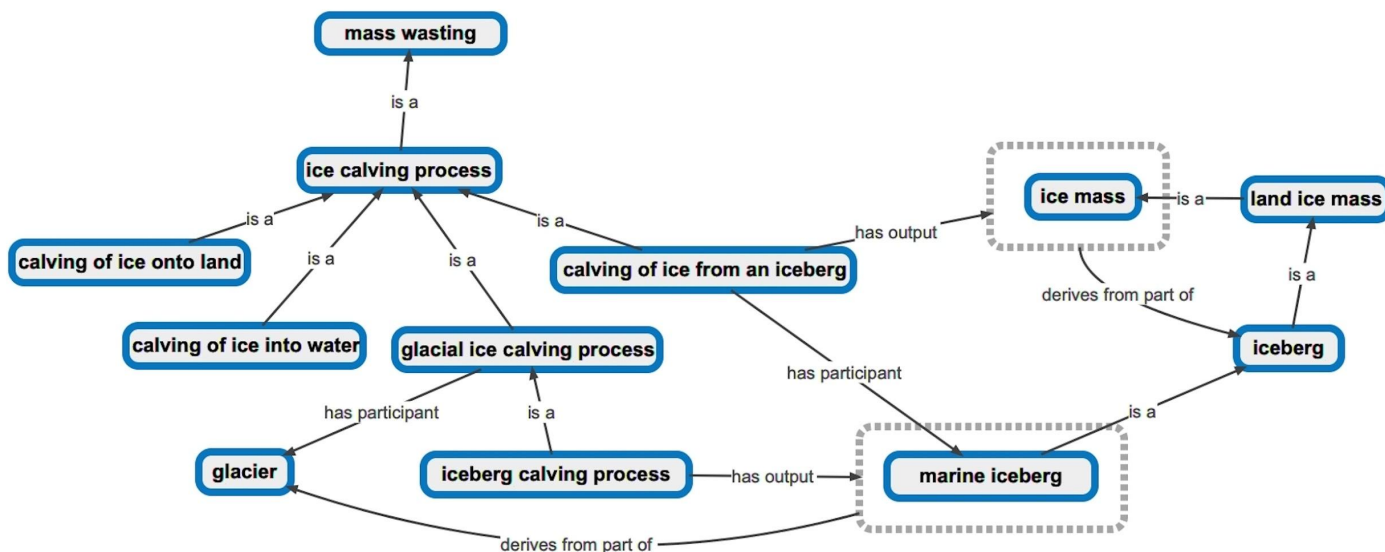


Figure 5: A partial ENVO representation of harmonized 'ice calving process' terms. Blue boxes represent terms within the ontology, the lines indicate subclass (i.e., is a) and other relationships between terms, while dotted gray boxes indicate that the enclosed terms inherit the relationships from other levels within the ontology.

Figure 5 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 differentia 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 implicitly obvious for domain scientists, but not apparent from their commonly-used labels. Similarly, 'Land ice', 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 skos:closeMatch which typically implies

that positioning within each hierarchy is comparable but that SWEET’s lack of definitions 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 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 skos:broad or skos:narrow matches indicating that one of the terms is less specific than the other. skos:broad matches provided the bulk of these types of matches indicating that the ENVO term was more specific than the SWEET term.

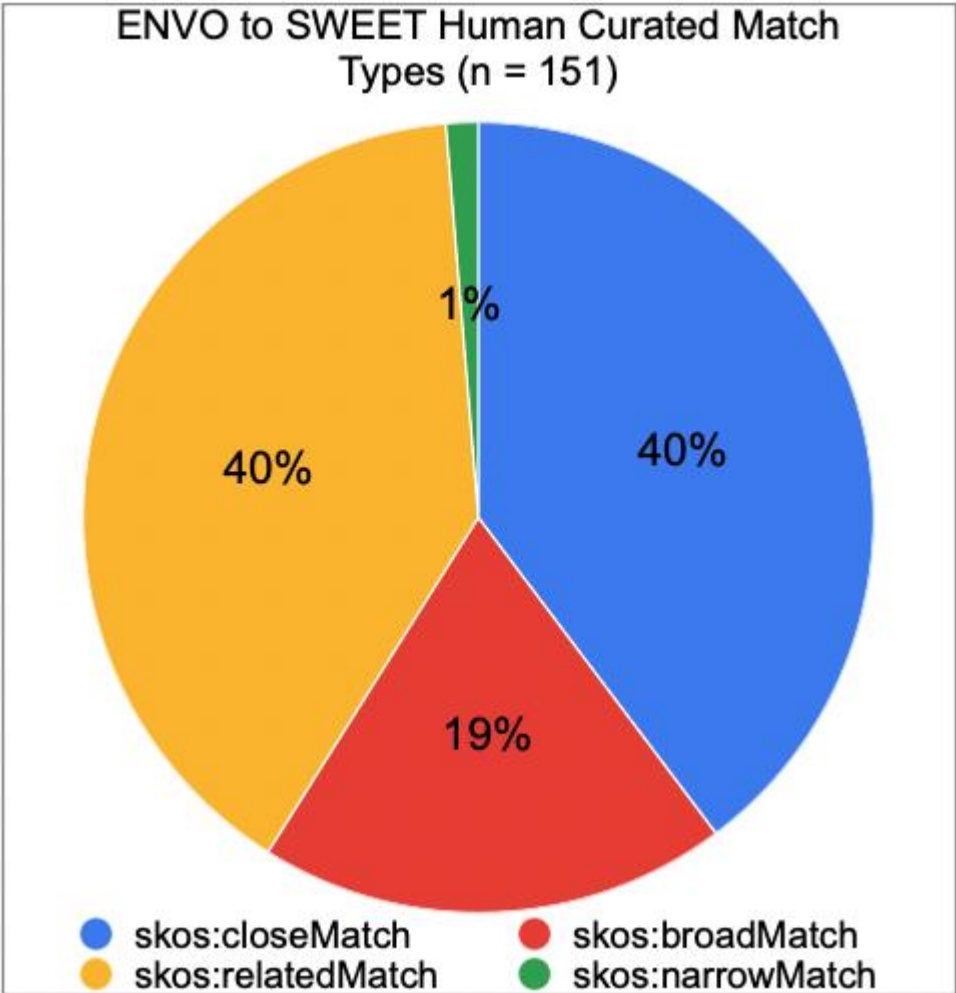


Figure 6: Match types in the SSSOM created for ENVO and SWEET

It is quite common in the field for folks to attempt lexical matching of concepts from multiple ontologies (Euzenat and Shvaiko, 2013; Liu et al, 2021), that is, matching based on similarity of the un-defined concept label only (or where the concept label is the most heavily weighted feature of the matching algorithm). 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 7, 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. Moreover, we note that the majority of the terms for which we assigned a relationship could not be matched based on their labels, since they had little or no lexical similarity.

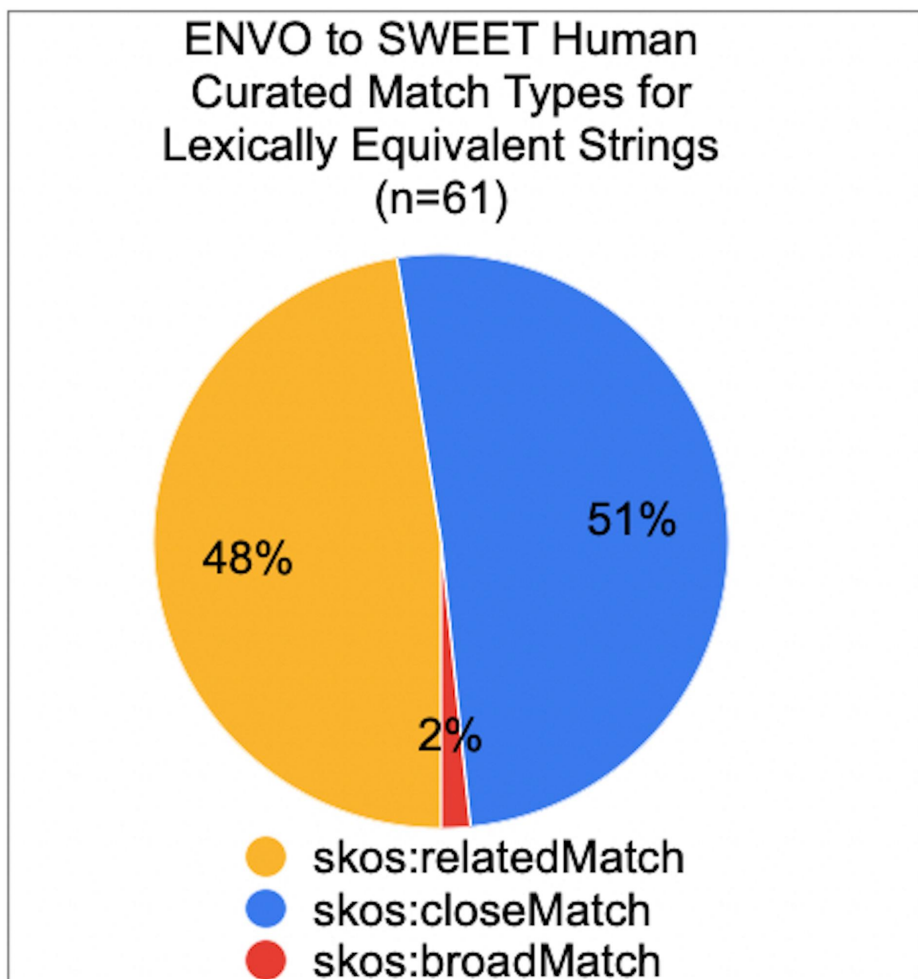


Figure 7: Match types for Lexically Equivalent Strings

As summarized in Figure 8, 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 called into question; GitHub issues have been created to address the concerns identified from these cases.

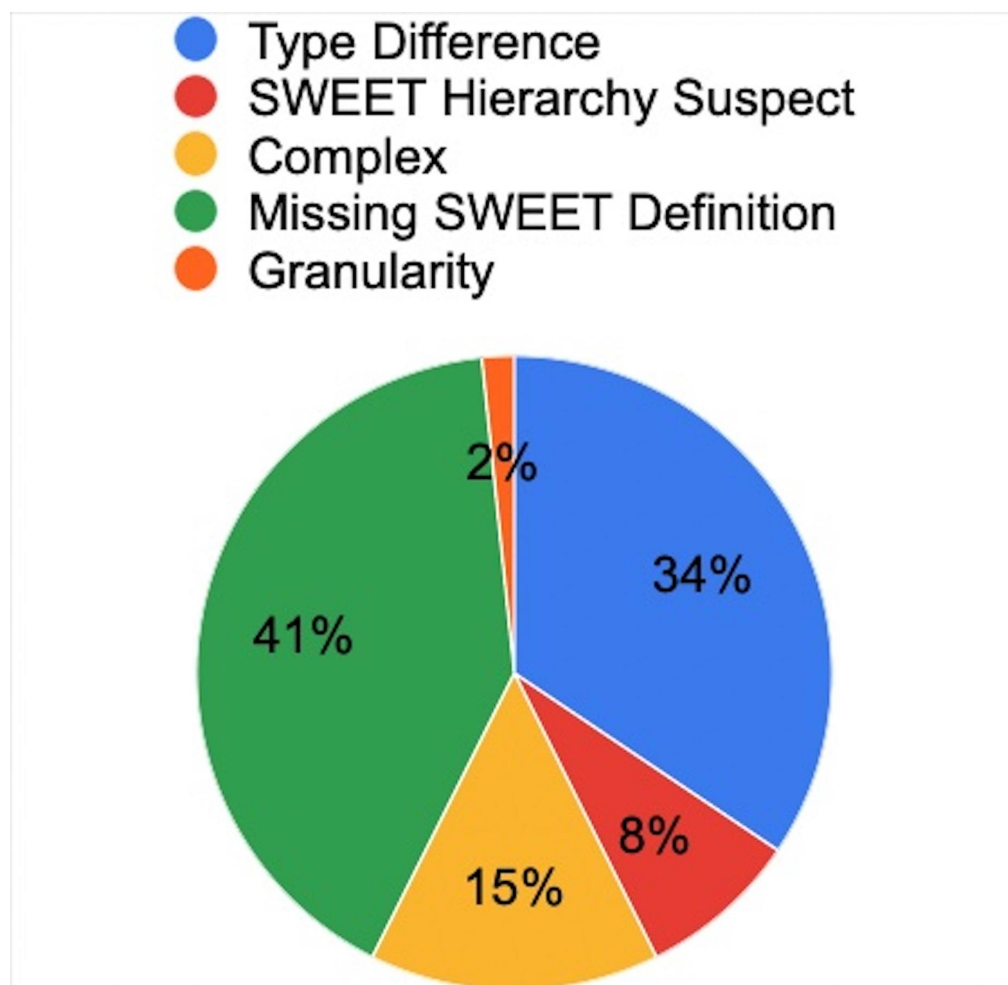


Figure 8: Reasons why lexically equivalent terms were not said to be semantically equivalent

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 2 depicts this general process using the GCW glossaries, ENVO and SWEET purely as examples of the types of resources that can be harmonized. A summary of the general process we developed follows:

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.
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

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 et al, 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 differences

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 concept able to account for all the variation and nuance of the more precise local variation as 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. 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, e.g. semantic drift. 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 concepts. Unfortunately, ontology modeling cannot resolve disputes in the domain of discourse. In these situations, resolution will ultimately 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, there are two courses of action, with only one being considered practical. The practical alternative involves 1) acknowledging the problem, 2) include terms in ontologies wherever their inclusion is absolutely required and 3) include a note with the term itself, possibly as a skos:scopeNote, as well as to the editor of the ontology, about the problem and the likelihood that the term's placement, axiomatization and/or inclusion may need to change in the future. The other option would be to create a separate ontology capturing the alternate world view, but this option is often considered wildly impractical.

## 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 (Seppälä et al, 2017). 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 Protégé (Musen, 2015). However, it is up to the ontology editor to 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.

Let's return to our example in Figure 5. The term 'calving' 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. 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 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, more general class. The rest of the sentence describes how this term is specialized from its parent. 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 (i.e., 'has participant' some 'water body').

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 surprising 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 were added 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'.

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 subclass under 'thickness' 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 each of the examples above, it was possible to generate a SSSOM relationship between the terms despite their differences.

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.

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. 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.

## 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', as discussed earlier. 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 other 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 lesson 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 processable 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.

<b>Domain</b>	<b>Description</b>	<b>Work Done To Date</b>
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: <ul style="list-style-type: none"> <li>● Geolocation: surface location, sample time, depth of sample</li> <li>● Soil organic carbon: bulk density, coarse fraction, organic fraction</li> <li>● Metals, salts, and acids: pH, elemental analysis, and ionic exchange</li> <li>● Nutrients: phosphorus and nitrogen</li> <li>● Gas flux: field respiration and incubation</li> <li>● Fractions: texture (sand/slit/clay) and sample subsetting (physicochemical fractionation)</li> <li>● Isotopes: Radiocarbon and other isotopes</li> </ul>
Coastal and Marine Ecological Classification Standard (CMECS)	Attempt to extend existing harmonization with ENVO	<ul style="list-style-type: none"> <li>● Assess domains where CMECS and ENVO can contribute additional terms to each other</li> <li>● Harmonize like terms in ENVO and CMECS</li> </ul>
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.
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## Conclusion

Alignment and semantic harmonization across the growing types of semantic resources is important for data interoperability and reuse, thus satisfying FAIR principles. 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

The authors have no competing interests to declare.

## References

- American Geophysical Union** n.d. Index of Terms. Available at <https://www.agu.org/Publish-with-AGU/Publish/Author-Resources/Index-terms> [Last accessed 11 November 2021].
- Arp, R, Smith, B, and Spear, A D** 2015 *Building Ontologies with Basic Formal Ontology*. London, UK: The MIT Press.
- Basic Formal Ontology 2019. Available at <https://github.com/BFO-ontology/BFO>
- Bates, R L and Jackson, J A** (eds.) 1984 *Dictionary of Geological Terms*. Third. Garden City, New York: Anchor Press/Doubleday.
- Blumberg, K, Chong, S, and Buttigieg, P L** 2021 Adding classes to ENVO. *GitHub*. Available at <https://github.com/EnvironmentOntology/envo/wiki/Adding-classes-to-ENVO> [Last accessed 19 December 2023].
- Blumberg, K and Duerr, R** 2022 ENVO Robot template and merge workflow. *GitHub*. Available at <https://github.com/EnvironmentOntology/envo/wiki/ENVO-Robot-template-and-merge-workflow> [Last accessed 19 December 2023].
- British Oceanographic Data Centre** 2023 The NERC Vocabulary Server. Natural Environment Research Council. Available at <https://vocab.nerc.ac.uk> [Last accessed 14 December 2023].
- Buttigieg, P L** 2021 Creating good definitions · EnvironmentOntology/envo Wiki. Available at <https://github.com/EnvironmentOntology/envo/wiki/Creating-good-definitions> [Last accessed 19 December 2023].
- Buttigieg, P L, Morrison, N, Smith, B, Mungall, C J, Lewis, S E, and the ENVO Consortium** 2013 The environment ontology: contextualising biological and biomedical entities. *Journal of Biomedical Semantics*, 4(1): 43. DOI: <https://doi.org/10.1186/2041-1480-4-43>
- Buttigieg, P L, Mungall, C, Duncan, B, Blumberg, K, Wilkie, I, meichen-liu, Meyer, R, Chong, S, Matentzoglou, N, Lauren, Laporte, M-A, diatomsRcool, Miller, M A, Douglass, E, Udaiwal, K, Hoyt, C T, Cox, S, Suzuki, S, Linares, J, Judkins, J, renzo, Antonarctica, Dooley, D, rduerr, ukaraoz, brandonw, and uberon** 2023 EnvironmentOntology/envo: 2023-02-13 release. DOI: <https://doi.org/10.5281/zenodo.7636736>
- Buttigieg, P L, Pafilis, E, Lewis, S E, Schildhauer, M P, Walls, R L, and Mungall, C J** 2016 The environment ontology in 2016: bridging domains with increased scope, semantic density, and interoperation. *Journal of biomedical semantics*, 7(1): 57–57. DOI: <https://doi.org/10.1186/s13326-016-0097-6>
- Duerr, R** 2023 ESIPFed/CRYO-Harmonization: Repository for ESIP semantic harmonization work on cryosphere terms. *ESIPFed/CRYO-Harmonization*. Available at <https://github.com/ESIPFed/CRYO-Harmonization> [Last accessed 19 December 2023].
- Duerr, R** 2018a WMO GCW Glossary Terms and their Alignment with Terms in Leading Semantic Resources. DOI: <https://doi.org/10.13140/RG.2.2.26770.12489>
- Duerr, R** 2018b WMO GCW Nomenclature Assessment. DOI: <https://doi.org/10.13140/RG.2.2.35158.73284>
- ESIPFed** 2023 ESIP Federation Community Ontology Repository Services. *ESIP Community Ontology Repository*. Available at <http://cor.esipfed.org/> [Last accessed 19 December 2023].
- Euzenat, J and Shvaiko, P** 2013 *Ontology Matching*. 2nd ed. Springer Berlin, Heidelberg. Available at <https://doi.org/10.1007/978-3-642-38721-0>
- FAIR Principle II 2015. *II: (Meta)data use a formal, accessible, shared, and broadly applicable language for knowledge representation*. Available at <https://www.go-fair.org/fair-principles/> [Last accessed 3 January 2023].
- FAIR Principles 2015. *FAIR Principles - GO FAIR*. Available at <https://www.go-fair.org/fair-principles/> [Last accessed 3 January 2023].
- FAIRsharing Team** 2015 FAIRsharing record for: Quantities, Units, Dimensions and Types. DOI:

<https://doi.org/10.25504/FAIRSHARING.D3PQW7>

**Gil, Y, Pierce, S A, Babaie, H, Banerjee, A, Borne, K, Bust, G, Cheatham, M, Ebert-Uphoff, I, Gomes, C, Hill, M, Horel, J, Hsu, L, Kinter, J, Knoblock, C, Krum, D, Kumar, V, Lermusiaux, P, Liu, Y, North, C, Pankratius, V, Peters, S, Plale, B, Pope, A, Ravela, S, Restrepo, J, Ridley, A, Samet, H, Shekhar, S, Skinner, K, Smyth, P, Tikoff, B, Yarmey, L, and Zhang, J** 2018 Intelligent Systems for Geosciences: An Essential Research Agenda. *Commun. ACM*, 62(1): 76–84. DOI: <https://doi.org/10.1145/3192335>

**Giunchiglia, F and Zaihrayeu, I** 2009 Lightweight Ontologies. In: Liu, L and Özsu, M T (eds.), *Encyclopedia of Database Systems*. Boston, MA: Springer US. pp. 1613–1619. DOI: [https://doi.org/10.1007/978-0-387-39940-9\\_1314](https://doi.org/10.1007/978-0-387-39940-9_1314)

**Haller, A, Janowicz, K, Cox, S J D, Lefrançois, M, Taylor, K, Le Phuoc, D, Lieberman, J, García-Castro, R, Atkinson, R, and Stadler, C** 2019 The modular SSN ontology: A joint W3C and OGC standard specifying the semantics of sensors, observations, sampling, and actuation. *Semantic Web*, 10(1): 9–32. DOI: <https://doi.org/10.3233/SW-180320>

Home - Earth Science Information Partners (ESIP) n.d. *ESIP*. Available at <https://www.esipfed.org/> [Last accessed 20 December 2023].

**Huntley, R P, Harris, M A, Alam-Faruque, Y, Blake, J A, Carbon, S, Dietze, H, Dimmer, E C, Foulger, R E, Hill, D P, Khodiyar, V K, Lock, A, Lomax, J, Lovering, R C, Mutowo-Meullenet, P, Sawford, T, Van Auken, K, Wood, V, and Mungall, C J** 2014 A method for increasing expressivity of Gene Ontology annotations using a compositional approach. *BMC bioinformatics*, 15: 155. DOI: <https://doi.org/10.1186/1471-2105-15-155>

**Jackson, R C, Balhoff, J P, Douglass, E, Harris, N L, Mungall, C J, and Overton, J A** 2019 ROBOT: A Tool for Automating Ontology Workflows. *BMC Bioinformatics*, 20(1): 407. DOI: <https://doi.org/10.1186/s12859-019-3002-3>

**Janowicz, K, Haller, A, Cox, S J D, Le Phuoc, D, and Lefrançois, M** 2019 SOSA: A lightweight ontology for sensors, observations, samples, and actuators. *Journal of Web Semantics*, 56: 1–10. DOI: <https://doi.org/10.1016/j.websem.2018.06.003>

**Lenton, T M, Armstrong McKay, D I, Loriani, S, Abrams, J F, Lade, S J, Donges, J F, Milkoreit, M, Powell, T, Smith, S R, and Zimm, C** 2023 The Global Tipping Points Report 2023. Available at <https://global-tipping-points.org/> [Last accessed 14 December 2023].

**Liu, Xiulei, Tong, Q, Liu, Xuhong, and Qin, Z** 2021 Ontology Matching: State of the Art, Future Challenges, and Thinking Based on Utilized Information. *IEEE Access*, 9: 91235–91243. DOI: <https://doi.org/10.1109/ACCESS.2021.3057081>

**Matentzoglou, N, Balhoff, J P, Bello, S M, Bizon, C, Brush, M, Callahan, T J, Chute, C G, Duncan, W D, Evelo, C T, Gabriel, D, Graybeal, J, Gray, A, Gyori, B M, Haendel, M, Harmse, H, Harris, N L, Harrow, I, Hegde, H B, Hoyt, A L, Hoyt, C T, Jiao, D, Jiménez-Ruiz, E, Jupp, S, Kim, H, Koehler, S, Liener, T, Long, Q, Malone, J, McLaughlin, J A, McMurry, J A, Moxon, S, Munoz-Torres, M C, Osumi-Sutherland, D, Overton, J A, Peters, B, Putman, T, Queralt-Rosinach, N, Shefchek, K, Solbrig, H, Thessen, A, Tudorache, T, Vasilevsky, N, Wagner, A H, and Mungall, C J** 2022 A Simple Standard for Sharing Ontological Mappings (SSSOM). *Database*, 2022: baac035. DOI: <https://doi.org/10.1093/database/baac035>

**McCreary, D** 2006 *Patterns of Semantic Integration*. Available at <https://www.slideshare.net/dmccreary/semint> [Last accessed 2 January 2023].

**McGibbney, L J, Whitehead, B, Rueda-Velásquez, C A, Duerr, R, Keil, J M, Berg-Cross, G, Rose, K, dr-shorthair, smrgeoinfo, graybeal, pbuttigieg, charlesvardeman, ashepherd, esip, nicholascar, ignazio1977, cmungall, esip-lab, and bradh** 2022 Semantic Web for Earth and Environmental Terminology (SWEET). Available at <http://sweetontology.net>

**Miles, A and Bechhofer, S** 2009 SKOS Simple Knowledge Organization System Reference. <http://www.w3.org/TR/skos-reference/>: *World Wide Web Consortium; 2009*. Available at <https://www.escholar.manchester.ac.uk/uk-ac-man-scw:66505> [Last accessed 19 December 2023].

**Mungall, C, Osumi-Sutherland, D, Overton, J A, Balhoff, J, Clare72, pgaudet, Brush, M,**

**Matentzoglou, N, Touré, V, Dooley, D, Sinclair, M, Bretaudeau, A, Cain, S, Haendel, M, diatomsRcool, Hammock, J, Laporte, M-A, Jensen, M, and Larralde, M** 2020 oborel/obo-relations: 2020-07-21. DOI: <https://doi.org/10.5281/zenodo.3955125>

**Musen, M A** 2015 The protégé project: a look back and a look forward. *AI Matters*, 1(4): 4–12. DOI: <https://doi.org/10.1145/2757001.2757003>

**Nagendra, K S, Bukhres, O, Sikkupparbathiyam, S, Areal, M, Miled, Z B, Olsen, L, Gokey, C, Kendig, D, Northcutt, T, Kordova, R, and Major, G** 2001 NASA Global Change Master Directory: an implementation of asynchronous management protocol in a heterogeneous distributed environment. In: *Proceedings 3rd International Symposium on Distributed Objects and Applications*. Presented at the Proceedings 3rd International Symposium on Distributed Objects and Applications. pp. 136–145. DOI: <https://doi.org/10.1109/DOA.2001.954079>

**Neuendorf, K K E, Mehl, Jr., J P, and Jackson, J A** 2011 *Glossary of Geology*. (Revised) Fifth; Version 1.9. American Geosciences Institute.

**NSIDC** n.d. hummock. *National Snow and Ice Data Center*. Available at <https://nsidc.org/learn/cryosphere-glossary/hummock> [Last accessed 19 December 2023].

**OBO Technical Working Group** 2022 OBO Foundry Principles. *Principles: Overview*. Available at <https://obofoundry.org/principles/fp-000-summary.html> [Last accessed 12 February 2023].

**Overton, J A, Dietze, H, Essaid, S, Osumi-Sutherland, D, and Mungall, C J** 2015 ROBOT: A command-line tool for ontology development. In: Couto, F M and Hastings, J (eds.), *Proceedings of the International Conference on Biomedical Ontology (ICBO 2015)*. Lisbon, Portugal: CEUR. p. 2. Available at <https://ceur-ws.org/Vol-1515/demo6.pdf>

**Raskin, R G and Pan, M J** 2005 Knowledge Representation in the Semantic Web for Earth and Environmental Terminology (SWEET). *Computers & Geosciences*, 31(9): 1119–1125. DOI: <http://dx.doi.org/10.1016/j.cageo.2004.12.004>

**Semantic Harmonization Cluster** 2023 ESIPFed/CRYO-Harmonization: Data for DSJ article. DOI: <https://doi.org/10.5281/zenodo.7939138>

**Seppälä, S, Ruttenberg, A, and Smith, B** 2017 Guidelines for writing definitions in ontologies. *Ciência da Informação*, 46(1): 73–88. DOI: <https://doi.org/10.18225/ci.inf.v46i1.4015>

**Shepherd, A, Jones, M, Richard, S, Jarboe, N, Vieglais, D, Fils, D, Duerr, R, Verhey, C, Minch, M, Mecum, B, and Nokome Bentley** 2022 Science-on-Schema.org v1.3.1. DOI: <https://doi.org/10.5281/ZENODO.7872383>

The Environment Ontology n.d. Available at <https://sites.google.com/site/environmentontology/> [Last accessed 3 January 2023].

USGS Thesaurus n.d. Available at <https://apps.usgs.gov/thesaurus/thesaurus-full.php>

**Whitehead, B** 2022 *SWEET Governance and Roadmapping: Survey Results*. DOI: <https://doi.org/10.6084/m9.figshare.20293860.v1>

**Wilkinson, M D, Dumontier, M, Aalbersberg, Ij J, Appleton, G, Axton, M, Baak, A, Blomberg, N, Boiten, J-W, Santos, L B da S, Bourne, P E, Bouwman, J, Brookes, A J, Clark, T, Crosas, M, Dillo, I, Dumon, O, Edmunds, S, Evelo, C T, Finkers, R, Gonzalez-Beltran, A, Gray, A J G, Groth, P, Goble, C, Grethe, J S, Heringa, J, Hoen, P A C 't, Hooft, R, Kuhn, T, Kok, R, Kok, J, Lusher, S J, Martone, M E, Mons, A, Packer, A L, Persson, B, Rocca-Serra, P, Roos, M, Schaik, R van, Sansone, S-A, Schultes, E, Sengstag, T, Slater, T, Strawn, G, Swertz, M A, Thompson, M, Lei, J van der, Mulligen, E van, Velterop, J, Waagmeester, A, Wittenburg, P, Wolstencroft, K, Zhao, J, and Mons, B** 2016 The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data*, 3(1): 160018. DOI: <https://doi.org/10.1038/sdata.2016.18>

**Wolodkin, A, Weiland, C, and Grieb, J** 2023 Mapping. bio: Piloting FAIR semantic mappings for biodiversity digital twins. *Biodiversity Information Science and Standards*, 7: e111979. Available at <https://biss.pensoft.net/article/111979/download/pdf/> [Last accessed 7 December 2023].

**Zeng, M L** 2008 Knowledge Organization Systems (KOS). *Knowledge Organization*, 35(3/2): 160–182.