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Spatially enabling the Global Framework for Climate Services: Reviewing geospatial solutions to efficiently share and integrate climate data & information

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ABSTRACT

In November 2016, the Paris Agreement entered into force calling Parties to strengthen their cooperation for enhancing adaptation and narrowing the gap between climate science and policy. Moreover, climate change has been identified as a central challenge for sustainable development by the United Nations 2030 Agenda for Sustainable Development.

Data provide the basis for a reliable scientific understanding and knowledge as well as the foundation for services that are required to take informed decisions. In consequence, there is an increasing need for translating the massive amount of climate data and information that already exists into customized tools, products and services to monitor the range of climate change impacts and their evolution. It is crucial that these data and information should be made available not in the way that they are collected, but in the way that they are being used by the largest audience possible.

Considering that climate data is part of the broader Earth observation and geospatial data domain, the aim of this paper is to review the state-of-the-art geospatial technologies that can support the delivery of efficient and effective climate services, and enhancing the value chain of climate data in support of the objectives of the Global Framework for Climate Services. The major benefit of spatially-enabling climate services is that it brings interoperability along the entire climate data value chain. It facilitates storing, visualizing, accessing, processing/analyzing, and integrating climate data and information and enables users to create value-added products and services.

1. Introduction

According to the WMO Statement on the Status of the Global Climate in 2015 (World Meteorlogical Organization, 2016), the globally averaged temperature over land and ocean surfaces for 2015 was the highest among all years since record keeping began in 1880. This is also the largest margin by which the annual global temperature has been reached. During the 21st Conference of Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCC) in Paris in 2015, countries have renewed their commitments to continue their efforts against global warming with the aim to limit the increase if possible to a maximum of 1.5 °C above preindustrial levels (UNFCCC, 2015). This requires a profound transformation moving towards resilient low carbon economies and implies substantial reductions of fossil fuel emissions of 80–95% by 2050; a complete phase-out by 2100; and significant adaptation efforts (Christoph et al., 2016).

To support this objective and continue to narrow the gap between climate science and policy, the Paris Agreement that entered into force in November 2016 calls Parties to strengthen their cooperation on enhancing action on adaptation. In particular, Articles 7(a) and (c) emphasize the need of improved sharing of information and *"Strengthening scientific knowledge on climate, including research, systematic observation of the climate system and early warning systems, in a manner that informs climate services and supports decision-making"* (UNFCCC, 2015). As a consequence, there is an increasing need for translating the massive amount of climate data and information that already exists into customized tools, products and services to monitor the range of climate change impacts and their evolution (Dolman et al., 2016).

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The importance of climate change as a central challenge for sustainable development has been reinforced by the United Nations 2030 Agenda for Sustainable Development (United Nations, 2012, 2015). This agenda is a plan for action articulated around 17 Sustainable Development Goals (SDGs). Climate change has been identified as one of the greatest global challenges our society is facing today. It is considered as a cross-cutting challenge in various SDGs that can undermine the ability of countries to achieve sustainable development, putting billions of people at risk and in particular the most vulnerable communities in less developed countries. Specifically related to climate change, Goal 13 is calling for urgent action to combat climate change and its impacts, while enhancing resilience of our societies to natural hazards and climate change and developing a sustainable low-carbon economy.

To address the Paris Agreement and SDGs challenges, timely and reliable access to data and information on the environment, how it evolves is essential. Data provide the basis for a reliable scientific understanding and knowledge as well as the foundation for services that are required to take informed decisions (Trenberth et al., 2016).

To answer this need, the Global Framework for Climate Services (GFCS) has been established by the United Nations and spearheaded by the World Meteorological Organization (WMO) to support the development and application of science-based climate information and services for effective decision-making (see Table 1 for a glossary of terms used in this paper). For the GFCS, climate services involve the production, translation, transfer, and use of climate data and information to support climate-informed decision-making, policy development and planning (World Meteorlogical Organization, 2011). The ultimate objective is to ensure that the best available climate science is effectively used and communicated to various sectors (e.g., agriculture, water, health) that may benefit from climate knowledge (Lucio et al., 2016). This requires accessing reliable national and international repositories of data such as temperature, precipitation, wind, soil moisture, or ocean conditions as well as assessments, projections, scenarios or vulnerability and risk analyses. Moreover, following users' needs, these data may be combined with other types of data like socioeconomic variables, health trends, and agricultural production or energy production (Swart et al., 2017).

Currently, the demand for climate services is lower than what is required to deliver the expected benefits so that the potential market is largely unrealized (Lourenço et al., 2016; Street, 2015). One of the main challenges that climate services have to face is to reduce the gap between climate science and decision-makers (Vaughan et al., 2016). Indeed, on the one hand, climate scientists are generally interested in an improved understanding of the processes that regulate the climate, while on the other hand, decision-makers need simple and easy to obtain knowledge for informed decision making. This has led to a disconnection between real and perceived needs of climate knowledge. Consequently, to close this gap, it is essential to have proper engagement and interactions between providers and users of climate information together with an effective data access mechanism to answer various user needs (Buontempo et al., 2014).

Achieving the objective of a sustainable development requires the integration of different data sets on physical, chemical, biological, and socio-economic systems coming from various sources (Lehmann et al., 2017). Collectively, these diverse data constitute a set of environmental attributes describing a specific location; they can therefore be considered to be part of geospatial data. Environmental data are valuable when combined with other data sets, e.g., social and economic, allowing one to monitor and assess the status of global, regional or local environments, to discover relationships between them, or to model future changes. To make sense of the huge amount of environmental data that exists and that is currently generated on a daily basis, it is essential to agree upon common standards to facilitate their sharing and integration. It is in this context that the concept of Spatial Data Infrastructure (SDI) has emerged. This term, first introduced by the U.S.

Table 1
A glossary of terms used in this paper.

Term	Context
Climate data (series)	A time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change (Committee on Climate Data Records from NOAA Operational Satellites, 2004). These data series can be generated by in situ measurements (e.g. ground-based sensor measurements), remote sensing (e.g., satellite observations) and models (e.g., predictions and projections)
Climate services	Climate information that assists decision making by individuals and organizations[a]
Essential Climate Variables (ECV)	An ECV is a physical, chemical or biological variable or a group of linked variables that critically contributes to the characterization of Earth' s climate[b] and support policy action
Data value chain	Information flow that describes a series of steps needed to generate value and useful insights from data (European Commission DG Connect, 2014). These steps includes: enhanced data discovery (e.g., capture, storage, organization), integration (e.g., visualization, access), and exploitation (e.g., transformation, analysis, tailored products and services)
Interoperability	The extent to which systems and devices can exchange data, and interpret that shared data. For two systems to be interoperable, they must be able to exchange data and subsequently present that data such that it can be understood by a user[c]
Standard	A document that provides rules or guidelines to achieve order in a given context[d]. In the domain of Information and Communication Technologies (ICT), standards address especially the needs for interconnection and interoperability. Standards are frequently referenced by regulators and legislators for protecting user and business interests, and in support of government policies.
Web service	A collection of operations offered by a provider to users, using the World Wide Web for communicating
Sustainable Development Goals (SDG)	A set of 17 goals to end poverty, protect the planet, and ensure prosperity for all as part of the United Nations Sustainable Development Agenda[e]
Group on Earth Observation (GEO)	The Group on Earth Observations (GEO) was established in 2005 as an intergovernmental mechanism for coordinating all existing and future Earth observations systems and implementing a "Global Earth Observation System of Systems" (GEOSS). It was launched in response to calls from the WSSD, the G8 and three ministerial Earth Observation Summits to improve existing Earth observation systems
Global Earth Observation System of Systems (GEOSS)	GEOSS is a set of coordinated, independent Earth observation, information and processing systems that interact and provide access to diverse information for a broad range of users in both public and private sectors. GEOSS links these systems to strengthen the monitoring of the state of the Earth. It facilitates the sharing of environmental data and information collected from the large array of observing systems contributed by countries and organizations within GEO

[a] http://www.wmo.int/gfcs/what_are_climate_weather_services.
[b] https://public.wmo.int/en/programmes/global-climate-observing-system/essential-climate-variables.
[c] http://www.himss.org/library/interoperability-standards/what-is-interoperability.
[d] http://www.etsi.org/standards/what-are-standards.
[e] http://www.un.org/sustainabledevelopment/sustainable-development-goals/.

National Research Council (National Research Council & Mapping Science Committee, 1993) denotes a framework to facilitate and coordinate provision and exchange of geospatial data encompassing different data sources, systems, networks, standards and organizations policies. The main goal is to deliver geospatial data and information from many diverse sources to the widest possible group of potential users. In 2005, the Group on Earth Observation (GEO[1]) was launched to build a global platform for sharing environmental data across several so-called Societal Benefit Areas (SBA) such as climate and weather. In 2007, the European Union (EU) adopted a directive (i.e. the INSPIRE Directive) to create a EU Spatial Data Infrastructure (European Commission, 2007). Several environmental disciplines (e.g., biodiversity, oceanography, hydrology) that have similar concerns regarding data accessibility, availability, compatibility, and integration have already embraced SDI concepts (Lehmann et al., 2014a,b). From a technological perspective, in the Web era, the fundamental condition to facilitate data exchange and integration is to agree on the use of open and standard protocols (i.e., operation interfaces and data encoding schemas) that enable systems interoperability to exchange and use information (Geraci, 1991; Open Geospatial Consortium, 2004).

Comparatively to other environmental sciences, climate-science is shifting more slowly to standard-based approaches (Woolf et al., 2005). It is still common to visualize maps and graphs as simple images and sharing data statically using FTP sites or download pages with various data formats. This lack of interoperability impedes efficient and effective integration of climate data and information with other data, products or applications. Consequently, it is difficult to answer the different needs and requirements of various climate data users and the value chain of climate data is not yet fully realized.

To tackle this data integration issue, it is essential to extend the definition of climate services with some architectural principles to ensure the provision of interoperable, flexible and efficient services and facilitate the discovery, access and use of climate-science data to a wide range of potential users. Considering that climate data is part of the broader Earth observation and geospatial data (United Nations, 2015), the aim of this paper is to review the state-of-the-art geospatial technologies that can support the delivery of efficient and effective climate services, enabling the value chain of climate data in support of the GFCS objectives (Fig. 1).

The remainder of the paper is structured as follows. Section 2 presents the GFCS and its objectives. Section 3 discusses the current status for delivering climate services by presenting various international, regional and national initiatives as well as some research projects. Section 4 presents the methodology for selecting the literature reviewed of geospatial standards and emerging technological concepts that can support the delivery of efficient and effective climate services. Section 5 expands the notion of service with a technological perspective and review challenges and possible solutions to better store and share climate data (5.1), improve data discovery (5.2), deal with data quality and uncertainty (5.3), cope with data visualization and download (5.4), improve data processing (5.5), facilitate integration (5.6), develop tailored products (5.7), and develop capacities (5.8). Based on this review, the Section 6 presents selected examples of increased use of interoperability in climate science. The Section 7 discusses benefits, limitations and perspectives of spatially-enabling the GFCS. Finally, the paper closes with conclusions and suggestions for more interoperable climate services.

2. The Global Framework for Climate Services (GFCS)

In 2009, at the Third World Climate Conference, the idea of a framework engaging climate scientists along with providers and users of climate data and information emerged. Experts were recognizing that current capabilities and mechanisms were not meeting present and future needs for providing effective access to science-based climate information (World Meteorlogical Organization, 2011). Consequently, thirteen heads of state or government, 81 ministers and 2500 scientists agreed to establish the GFCS supervised by the WMO to strengthen the production, availability, delivery of science-based climate information and services and to coordinate the development, implementation and application of climate products to support decision-making (Huges, 2011). The vision of the GFCS[2] is to enable society to better manage the risks and opportunities arising from climate variability and change, especially for those who are most vulnerable to such risks. This must be done through the development and incorporation of science-based climate information and prediction into planning, policy and practice. The greatest value of the GFCS should occur incrementally through the delivery of a multitude of climate services at various scales (e.g., from local to global).

Several drawbacks in climate data delivery and integration have been identified and these findings have served as foundations for the GFCS (World Meteorlogical Organization, 2011). It has been recognized that:

(1) Climate services do not efficiently exploit scientific climate knowledge, information and data;
(2) Climate services do not meet present and future user needs and in particular in developing or least developed countries that are the most vulnerable;
(3) Providers of climate services do not interact sufficiently with users;
(4) Existing capacities for climate observations provide a good basis for strengthening climate services but commitment to sustain high-quality observations across the entire climate system is inadequate;
(5) Enhancements in observations networks in developing countries are required;
(6) Restrictions about the sharing and access to data and information are a major barrier to progress and wide use of climate knowledge;
(7) Use of climate knowledge that can inform decision-making is inadequate and is not following the rapid advancement of the understanding of climate system; and
(8) Capacities of users is often insufficient to adequately use climate data and information.

The High-Level Taskforce on the GFCS defines climate services as a range of activities that is aiming at generating and providing information in a way that assists decision-making by individuals and organizations based on past, present and future of climate and on its impacts on natural and human systems (Lucio et al., 2016).

The central principle guiding the implementation of the GFCS is that it should serve the widest audience possible and in particular climate-vulnerable developing countries. The objectives of the GFCS are (1) to improve climate services for all countries, (2) build capacities of providers and users, (3) enable governments to have a central role as primary sources of climate services, (4) promote a free and open exchange of climate data and information while respecting existing data policies, (5) facilitate the timely access to relevant scientific information to help society to cope with current climate variability and limit economic and social damages caused by climate-related disasters.

The priority areas[3] for action are agriculture and food security, water management, disaster risk reduction, energy, and health. These five areas are recognized as key sectors where the GFCS can play a major role for climate change adaptation and mitigation and sustainable development. They are aligned with the needs and objectives of initiatives like the Sustainable Development Goals, the Hyogo Framework for Action, the Water-Food-Energy Nexus (Hoff, 2011), or the

[1] http://www.earthobservations.org.

[2] http://www.gfcs-climate.org/vision.

[3] http://www.gfcs-climate.org/priority-areas.

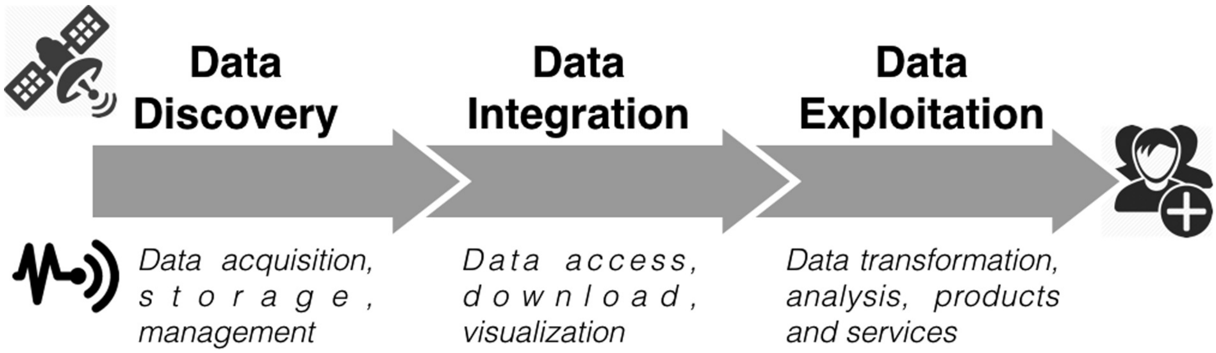

Fig. 1. Value chain of climate data: from data acquisition to end-users.

UNFCCC (Hewitt et al., 2012).

To strengthen the provision and use of climate predictions, products, information, data from local to global scales, the GFCS[4,5] relies on five main components (Fig. 2) (Hewitt et al., 2012):

The following height principles[6] are being used to guide the implementation of the GFCS:

(1) High priority for the needs of climate-vulnerable developing countries;
(2) Primary focus is the better access and use of climate information by users;
(3) The Framework addresses needs at three spatial scales: global, regional and national;
(4) Climate services must be operational and continuously updated;
(5) Climate information is primarily an international public good and governments will have a central role in the Framework;
(6) The Framework encourages global, free and open exchange of climate-relevant data;
(7) The Framework facilitates and strengthens – and does not duplicate efforts; and
(8) The Framework is built through partnerships.

The GFCS is aiming at supporting and fostering collaboration between global, regional and national initiatives and stakeholders (Hewitt et al., 2012). At the global level, the objective is to define large-scale activities necessary for delivering and developing climate services. At the regional scale, the focus is on strengthening cooperation and engaging with multilateral efforts to address regional needs (e.g., infrastructure development, data and information exchange, capacity building, research and training). Finally, at the national scale, the GFCS aims at ensuring effective coordination mechanisms by each national government to involve all relevant stakeholders to indicate their requirements for climate services.

To ensure that climate services answer users' needs an appropriate mechanism needs to be established that require technical capacities and active communication and exchange between data and information producers, translators, and community of users. Central to this task is the former Climate Information and Prediction Services (CLIPS). So far, CLIPS was the tool used by WMO to provide access to climate information. It has been recently closed and assimilated in the GFCS within the Climate Services Information System (CSIS) (Srinivasan et al., 2015). CLIPS has various elements that can be useful for the CSIS. It provides data management facilities as well as delivery mechanism for accessing climate monitoring and assessments, climate predictions and projections. It also provides a dedicated user interface for climate adaptation and risk management. However, this Information System does not implement any interoperability arrangements.

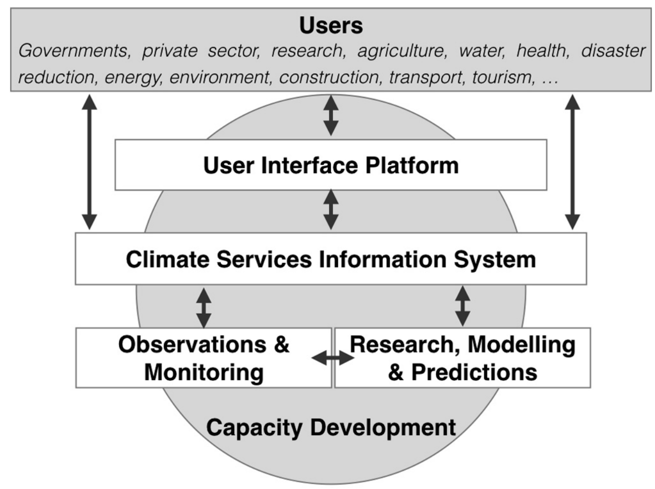

Fig. 2. The components of the GFCS and their relations (Adapted from World Meteorological Organization, 2011). The User Interface Platform is aiming at enabling users, researchers, and providers of climate services to interact to maximize the significance of climate services and lead to the development of applications that answers user needs. The Climate Services Information System should provide an effective mechanism to access and distribute climate data and information needed by users in accordance with rules, procedures, and restrictions agreed by data providers. The Observations and Monitoring component should ensure the generation climate observations necessary to meet the needs of climate services users and providers. The Research, Modeling, and Predictions component will assess and promote the development of climate prediction tools, products and the promotion of climate services in research agendas. Finally, the Capacity Building component is an overarching component aiming at supporting systematic capacity development of institutional, infrastructure and human resources.

Crucial for the success of the GFCS is building partnerships and obtaining the active engagement of major organizations by involving and receiving strong commitments from governments and agencies in the governance and implementation processes. The major challenge for GFCS is to gain recognition from governments that climate services have substantial value and deserve support (Hewitt et al., 2012). In particular, due to the global scale of climate change and its relationship with sustainable development, GFCS requires an international coordination. In its initial phase, the GFCS concentrated on developing and delivering services in the five priority areas where improved access to science-based climate knowledge can have immediate impacts in improving human safety and well-being (Hewitt et al., 2012). In term of governance, the main body is the Intergovernmental Board on Climate Services (IBCS), supported by a Management Committee for carrying out the decisions and requests of the Board; a Partner Advisory Committee (PAC) for stakeholder engagement; and a technical committee. To start developing capabilities at national and regional levels and engaging with user communities, the GFCS is supporting several

[4] http://www.wmo.int/pages/themes/climate/climate_services.php.
[5] http://www.gfcs-climate.org/components-of-gfcs.
[6] http://www.gfcs-climate.org/principles.

projects (http://www.wmo.int/gfcs/projects-map) with a particular attention on six countries (Bhutan, Burkina Faso, Dominica, Moldova, Papua New Guinea and Tanzania). This will help to highlight the benefits of collaboration and gather lessons learnt for replication of good practices in other countries. The ultimate objective is that by 2021, the GFCS should be fully operational and climate services should be widely used especially in climate-sensitive sectors.

3. Current situation in delivering climate services

3.1. Current situation at various scales

Currently, governments and agencies in every region of the world are already providing or developing a wide range of climate services for various sectors such as agriculture, water, health, disaster risk reduction, energy, transport and infrastructure, ecosystems, and urban issues (World Meteorological Organization, 2012). This wealth of services represents a solid foundation on which GFCS can rely to advance improvements in the provision of services tailored to users' needs. For example, the European Space Agency (ESA) Climate Change Initiative (CCI)[7] or the Committee on Earth Observation Satellites (CEOS) Working Group Climate (WGClimate)[8] are coordinating efforts to make full use of Earth Observations space assets to exploit long-term records on Essential Climate Variables (ECV) (Hollmann et al., 2013). In particular, the CEOS WGClimate has written a report on satellite observations for climate monitoring and the need for an international architecture that ensures timely delivery of observations for an efficient and effective analysis of the Earth's climate system (Dowell et al., 2013).

At the global scale, the Group on Earth Observations (GEO) Forest Carbon Tracking initiative[9] (that is part of the broader Global Forest Observation Initiative (GFOI)) is integrating in-situ observations and remote sensing data to estimate forest cover and carbon content. The main objective is to provide a set of monitoring, reporting and verifications tools to support climate mitigation policies. Another initiative also led by GEO is the Global Agricultural Monitoring (GEOGLAM[10]) aiming at providing reliable, accurate, timely and sustained crop monitoring information and yield forecasts. Monitoring crop conditions within countries at risk of food security, the GEOGLAM Early Warning Crop Monitor[11] can contribute to track SDG Goal 2 to *"End hunger, achieve food security and improved nutrition, and promote sustainable agriculture"* and in particular target 2c to adopt measures to ensure the proper functioning of food commodity markets and their derivatives, and facilitate timely access to market information, including food reserves, to help limit extreme food price volatility.

At the regional scale, the European funded the PRUDENCE[12] and ENSEMBLES[13] projects aimed to provide high resolution, quality controlled regional climate ensembles of predictions and link them to a wide range of applications (e.g., agriculture, health, water, food security). The European Climate Adaptation Platform (CLIMATE-ADAPT)[14] is a joint effort between the European Commission (EC) and the European Environment Agency (EEA) to support Europe in adapting to climate change by helping users to access and share data and information on expected impacts; vulnerability of regions and activities; adaptation strategies, options, actions and tools. Recently launched, the Copernicus Climate Change Service (C3S)[15] will be the major contribution from the European Union to the GFCS in particular for the *Observations and Monitoring* component.

At the national scale, various countries have already embraced the concept of climate services to support National Adaption Plans (NAP) (i.e., the means for identifying medium to long-term adaptation needs and developing and implementing strategies to address these needs) like the United States Climate.gov[16], the National Centre for Climate Services in Switzerland (NCCS)[17], the German Climate Portal[18], the Climate Service Center Germany (GERICS)[19] or the Southern African Development Community Climate Services Centre (SADC CSC)[20]. This indicates that at the three levels targeted by the GFCS several on-going initiatives are aiming to provide climate services.

3.2. Networks of end users, providers and researchers

All these efforts at different scales are complemented by interdisciplinary networks of climate information users, providers and researchers who are interested in climate services and are actively involved in the community. Such efforts are represented by the Climate Services Partnership[21], JPI-Climate[22], or CORDEX[23] (Giorgi et al., 2009). In addition, several research projects are complementing these institutional efforts for advancing the vision of climate services like IS-ENES2[24] for Earth System Modeling (Valcke et al., 2015), the IMPACT2C[25] on quantifying projected impacts under 2 °C warming (Preuschmann et al., n.d.), MARCO[26] for giving insights into the climate services market in Europe, ERA4CS[27] for boosting the development of efficient Climate Services (Kotova et al., 2017), or ANYWHERE[28] (EnhANcing emergencY management and response to extreme WeatHER and climate Events) to respond more rapidly than today to extreme climate and weather events. For additional examples of services and delivery structures readers can refer to Vaughan and Dessai (2014) and Medri et al. (2012).

3.3. Main climate data standards used

These examples demonstrate that the volume of climate data worldwide is expanding rapidly, thereby generating challenges in term of archiving, sharing, discovering, accessing and integrating it (Overpeck et al., 2011). These data usually documents past, present and future conditions of the climate system and are generated by models (e.g., predictions, projections), remote sensing (e.g., satellite observations), and in situ measurements. Most climate data are encoded using the netCDF (Network Common Data Format) model and format, defined by Unidata, following the CF (Climate and Forecast) conventions to formalize the necessary semantics as metadata (Domenico and Nativi, 2012). Alternatively, ASCII file formats are well adopted and the File Transfer Protocol (FTP) is widely used to transfer data. Climate data are commonly visualized as tables, graphs or maps. Overpeck et al. (2011) stated that the two major pressing issues for climate science concerning data are (1) ensuring the ever-growing volumes of data are easily and freely accessible to facilitate new scientific research, and (2) guarantee that these data and the information and knowledge generated from them are useful and understandable by a large interdisciplinary

[7] http://cci.esa.int/data.
[8] http://ceos.org/ourwork/workinggroups/climate/current-activities/.
[9] http://www.gfoi.org/rd/forest-carbon-tracking/.
[10] http://www.earthobservations.org/geoglam.php.
[11] http://www.geoglam-crop-monitor.org.
[12] http://prudence.dmi.dk/main.html.
[13] http://ensembles-eu.metoffice.com.
[14] http://climate-adapt.eea.europa.eu/about.
[15] http://climate.copernicus.eu.
[16] https://www.climate.gov.
[17] http://www.meteoswiss.admin.ch/home/research-and-cooperation/nccs.html.
[18] http://www.deutschesklimaportal.de/EN/Home/home_node.html.
[19] http://www.climate-service-center.de.
[20] http://www.sadc.int/sadc-secretariat/services-centres/climate-services-centre/.
[21] http://www.climate-services.org/.
[22] http://www.jpi-climate.eu/home.
[23] http://www.cordex.org.
[24] https://is.enes.org.
[25] http://impact2c.eu
[26] http://marco-h2020.eu.
[27] http://www.jpi-climate.eu/ERA4CS.
[28] http://anywhere-h2020.eu.

audience.

To monitor and understand the causes of climate change, identify potential impacts, evaluate options for adaptation and mitigation, and characterize extreme events (e.g., floods, droughts) global high-quality comprehensive and coordinated observations are necessary. Without such a baseline, it will be difficult to meet the various climate data user's requirements and developed tailored products for policy maker or stakeholders (Sessa and Latham, 2008). Moreover, these data are not only essential for climate science but they are also required for other environmental and sustainability disciplines (e.g., Ecosystem Services, Sustainable Development Goals, Nexus).

3.4. The Global Climate Observing System and Essential Climate Variables

The Global Climate Observing System (GCOS) is a joint undertaking of WMO, UNEP, the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational Scientific and Cultural Organization (UNESCO) and the International Council for Science (ICSU). GCOS has been established in 1992 to support IPCC with the objective of ensuring that observational data required for addressing climate-related issues are available to all potential users (Ostensen et al., 2008). GCOS has identified 50 Essential Climate Variables (ECVs[29]) that are required to support the work of the UNFCCC and the IPCC. These ECVs are technically and economically feasible for systematic observation (Bojinski et al., 2014). They can be measured using satellite remote sensing or terrestrial, atmospheric, and oceanographic sampling (Ostensen et al., 2008). These ECVs are essential data for delivering climate services and they are already widely adopted within science and policy domains (Bojinski et al., 2014). To facilitate and provide an effective access mechanism to ECVs, GCOS has initiated the Global Observing Systems Information Center (GOSIC) (Diamond and Lief, 2009). The GOSIC portal[30] is a clearinghouse (i.e., does not hold data) acting as a centralized entry-point to access data and information for GCOS. It enables users to search and access data in a harmonized and integrated way across multiple data repositories. Various matrices have been developed to provide rapid overviews and access to relevant data (Diamond and Lief, 2009) for both terrestrial and oceanic systems. Most interestingly, GOSIC has also designed an ECV Data Access Matrix[31].

Even if this represents an important step towards supporting data access for climate services, this ECV Data Access Matrix presents several drawbacks. It helps data users to identify repositories, however it is probably not enough to provide a service that can meet different expectations from various user communities. Indeed, it does not provide any search functionality, it is not possible to visualize the datasets, users have to deal with various data formats (e.g., NetCDF, ASCII file, CSV, GeoTIFF) and various data access methodologies (e.g., FTP, Web Accessible Folders, RESTful services, download pages), data are often not in the same spatial coordinate projection and temporal resolution and therefore should be transformed to be ready to be ingested in a model (e.g. data processing) or to be integrated with other data to better assess environmental conditions in a given region. In other words, this requires a lot of work before analyzing data and transform into useful information. Several studies (European Commission, 2015; Overpeck et al., 2011; Street, 2015) have identified data and information sharing and their related technical challenges as essential to strengthen the provider-user interface (Vaughan et al., 2016). Their aim is to provide reliable, usable, fit-for-purpose services that will help integrating climate information with multiple data sources within a multi-disciplinary framework.

[29] https://www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables.

[30] https://www.ncdc.noaa.gov/gosic.

[31] https://www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix.

3.5. Climate services and the geospatial community

Considering the fact that climate data are describing a location/region of the Earth through a set of attributes, they can be thought of as being part of geospatial data. In the geospatial community, a framework enabling connection between data providers and users is traditionally known as SDI. This promotes the use of a common (web-based) services bus that enables systems interoperability. This set of common services facilitates discovery, access and use of data for the whole infrastructure. Service-based interoperability is achieved through the recognition and implementation of well-defined interface protocols, which are specified by international (or sometimes Community) standards. Consequently, many of the international standards (i.e. OGC, ISO, and at a certain extent W3C) as well as the current research in the field of system-of-systems interoperability (e.g. software ecosystems) can significantly help GFCS to strengthen the provider-user interface and enhance the quality and relevance of climate services.

In the next section, we will review significant geospatial standards and emerging technological concepts that could benefit to spatially-enabled the GFCS, expand the notion of service with a technological perspective, enhance the quality and relevance of climate services, and help deliver efficient services that can be used in a multi-disciplinary framework.

4. Methodology

The review presented in this paper follows the general methodology proposed for systematic reviews (Collaboration for Environmental Evidence, 2013; Pullin and Stewart, 2006). This type of review is particularly useful when a subject is the focus of considerable research in recent years and where a comprehensive view can be useful for orienting future research and methods (Plummer et al., 2012). This is the case for climate services and in particular of accessing climate data in various disciplines. The objective of this study is to get a picture of the use of geospatial standards in relation with climate services and capture what are the benefits, limitations and perspectives in using geospatial technologies to support the delivery of efficient and effective climate services, and enhancing the value chain of climate data in support of the GFCS objectives.

The approach taken for searching relevant peer-reviewed and non-peer-reviewed literature consisted of a set of keywords used to query different repositories such as scientific libraries (e.g., Science Direct, Web of Knowledge, Google Scholar), personal databases of the researchers and their research groups, and the Internet (e.g., Google searches). These searches were not limited by geographical extent or scale. The following list of keywords were used individually for each query: '*climate services*', '*ogc*', '*interoperability*', '*essential climate variables*', '*geoss*', '*climate data*' producing a comprehensive list of articles. To refine results three additional criteria were used: articles should address climate services as the main or secondary subject; the keywords should be at least in the title, keywords or abstract; and articles should be written in English. Finally, following the recommendations for Internet searches the first 50 records were examined while the subsequent 50 were looked at for relevance (Collaboration for Environmental Evidence, 2013).

The combined results of these various searches account for more than 250 references over the last two decades. About 120 papers were excluded because they were beyond the scope of this study. The remaining articles were filtered manually to avoid duplications and screened to ensure that they are relevant to the climate data value chain. The final list of papers (about 70) were then categorized according to identified challenges that prevent interoperability along the data value chain.

5. Spatially-enabling the GFCS through standards and data value chains

From an architectural point of view, a fundamental requirement for delivering efficient climate services is to ensure that datasets are compatible among data producers by adopting standard specifications supported by different organizations. It is only through consistent and harmonized datasets that a multi-organizations community can expect effective data, which is required to achieve user objectives by responding to their needs (Sessa and Latham, 2008).

Recognizing that climate data is an essential resource for environmental research and sustainability assessment, it is necessary to coordinate all actions in a coherent workflow (i.e. data value chain), from data acquisition to knowledge generation for decision making, and to serve a wide range of stakeholders by supporting their technologies (Miller and Mork, 2013).

Such a data value chain will help creating and building value through enhanced data discovery (e.g., acquisition, storage, management), integration (e.g., access, download, visualization), and exploitation (e.g., transformation, analysis, tailored products and services). To ensure that measurements, observations, model outputs and predictions are meaningful and sustainable, standard schemes of data content can help in documenting, searching, accessing, interpreting, and integrating climate data and ultimately strengthening the interoperability interface between providers and users (Ostensen et al., 2008).

The Open Geospatial Consortium (OGC[32]) and the International Organization for Standardization (ISO)/Technical Committee (TC) 211 Geographic Information/Geomatics[33] are the leading international organizations developing a suite of open standards for modeling and implementing geospatial information interoperability. These standards can pave the way to meaningful data interoperability in climate science and help delivering and leveraging the power of climate services building discovery, access and use services for climate datasets and information (Woolf et al., 2005; Woolf et al., 2006).

5.1. Struggling with data formats, storage and sharing

The first element to consider in the data value chain is related to data acquisition, storage and management. Climate datasets can be typically considered as “Big Data”. Big data can be characterized according to their features represented in a four-dimensional space: Volume, Velocity, Variety and Veracity (Gijzen, 2013; Lee and Kang, 2015; UN Global Pulse, 2012). In terms of volume, Climate Data Centers usually handle Petabytes of data. These data arise from an almost continuous stream of diverse sources such as in-situ sensor measurements (e.g., temperature, precipitation, wind); remote sensing observations (e.g., satellite, aircraft, Unmanned Aerial Vehicle (UAV)), and climate models (e.g., predictions, projections).

As for variety, climate datasets are commonly encoded using different content models and formats, such as ASCII files, CSV (Comma Separated Values) files, and netCDF binary files for multi-dimensional and array-oriented scientific datasets. NetCDF, generally extended with the CF conventions, is particularly well suited, as it supports also the time dimension which is very important in climate science (Domenico and Nativi, 2012).

Finally, the veracity (e.g., data and model quality and uncertainty) of the huge amount of shared data is often an important issue to efficiently (re-)use climate data in the policy arena (Bastin et al., 2013). In particular, uncertainty is a major concern in ensemble forecasting, a commonly used method that involves multiple forecasts created with an individual forecast model by using different physical parameterizations or varying initial conditions to generate a representative sample of the possible future states of weather or climate (Palmer, 2000).

Several solutions exist to facilitate the storage, management, publishing and sharing of Big Climate Data. For example, the Raster Data Manager (Rasdaman) is an array analytics engine built on top of the PostgreSQL Database Management System that helps storing, analyzing and publishing multidimensional arrays using various open standards (Baumann et al., 1999; Baumann et al., 2016). Alternatively, THREDDS – Thematic Real-time Environmental Distributed Data Services (Domenico et al., 2002) and GeoServer[34] can easily publish netCDF (and other data formats) and expose these datasets using open standards (Nativi et al., 2006).

5.2. Documenting data to strength data discovery

In the data value chain pattern, the primary action that users undertake is to search for data that are suitable for their purpose. Therefore, enabling users to find and evaluate datasets before accessing them is an essential task. Effective and efficient data discovery relies on the existence of catalogs containing quality (i.e., full and updated) information describing datasets to be shared (Giuliani et al., 2016a) (Santoro et al., 2012). This information is referred to as discovery metadata. The importance of having discovery metadata catalogs is emphasized by major data sharing initiatives such as GEOSS – Global Earth Observation System of Systems (Nativi and Bigagli, 2009), INSPIRE (European Commission, 2007) and NSDI (National Research Council, 1993). It was recently reinforced by Open Data policies (Wessels et al., 2014). All these initiatives highlight the need to use data description specifications (i.e. metadata standards) to document datasets for searching, evaluating, and using (i.e., discovery, evaluate, and use metadata types). Interoperable catalogs implement open and standard metadata schemas that can be exchanged and used by different data systems for diverse scopes.

Several open standard schemas can be used to describe a given geospatial dataset. The most commonly used are those developed by ISO TC211, such as the abstract data and service description models ISO 19115 (*Geographic information – Metadata*)[35] and ISO 19119 (*Geographic information – Services*)[36] and their schema implementation ISO 19139 (*Geographic information – Metadata – XML schema implementation*)[37]. Several profiles are based on these, like the Federal Geographic Data Committee (FGDC)[38] specifications and the INSPIRE metadata ones (European Commission, 2008). Alternatively, the Dublin Core Metadata Initiative[39] and the related W3 C DCAT[40] specifications are more general standards (referring to any online resource) that are also widely used.

Once data are properly documented, the documentation records (i.e. metadata records) should then be stored in a catalog software component, which provides standardized search and discovery operations. For interoperability sake, these catalogs are requested to expose at least a standard interface for exposing its geospatial records on the Web. The OGC Catalog Service for the Web (CSW) is a well-implemented standard that enables users to discover, browse, and query metadata describing geospatial data, services and other resource types (Open Geospatial Consortium, 2007a). Alternatively, OpenSearch APIs[41] and its OGC profiles for geospatial information[42] can be used. These different metadata models and catalog interface standards offer a

[32] http://www.opengeospatial.org.
[33] http://www.isotc211.org.
[34] http://geoserver.org.
[35] http://www.iso.org/iso/catalogue_detail?csnumber=26020.
[36] http://www.iso.org/iso/catalogue_detail.htm?csnumber=39890.
[37] http://www.iso.org/iso/catalogue_detail.htm?csnumber=32557.
[38] https://www.fgdc.gov/metadata/geospatial-metadata-standards.
[39] http://dublincore.org.
[40] https://www.w3.org/TR/vocab-dcat/.
[41] http://www.opensearch.org/Home.
[42] http://www.opengeospatial.org/standards/opensearchgeo.

coherent framework for data documentation and discovery.

Unidata THREDDS Data Server (TDS)[43] has several capabilities to expose netCDF metadata; one of them provides an ISO 19115 metadata representation of the datasets' structure and description (Chengfang et al., 2009). GeoServer offers similar capabilities through a CSW interface. Additionally, interesting work has been undertaken in the context of the EU FP7 project CHARMe[44] (Characterization of metadata to enable high-quality climate applications and services) that has developed the concept of commentary metadata. The objective is to link climate datasets with publications, citations, assessments, user feedback to help users learn from previous experiences and select the best datasets that can suit their needs as well as providing a direct traceability between conclusions and data that supported them (Blower et al., 2013). Finally, discovery enhancement by metadata augmentation (e.g. semantic annotation and inferences, user tagging and feedbacks, etc.) is a vibrant research and innovation area that is promising to significantly advance geospatial data discoverability.

5.3. Dealing with data quality and uncertainties

Facilitating data discovery and access is necessary but not sufficient. Data quality and uncertainty is essential to enhance communication, accountability, and support efficient decision-making processes (European Commission, 2015; Moges et al., 2016; Street, 2015). Climatology is dependent on heterogeneous data sources, therefore inherited errors (e.g., accuracy) and uncertainties due to the various methods (e.g., downscaling methods necessary to process the data at the geographic and temporal scales needed for impact studies) used to create datasets and run models are important topics to consider (Kaye et al., 2012; Otto et al., 2015). Having means to ensure that quality and uncertainties are understood correctly can help informing adaptation and mitigation policies. Therefore, managing data and model uncertainty and quality in web-based frameworks is an important issue (Bastin et al., 2013). It is particularly true when we consider that policy and decision-makers are increasingly relying on scientific datasets and models to explore different scenarios to develop and/or take better informed decisions (Buytaert et al., 2012). Providing incomplete information can negatively influence decision-making and lead to the development of policies and strategies that are not responding the challenges we are facing (Otto et al., 2015). Consequently, effective instruments to quantify and efficiently communicate quality and uncertainties are essential.

As to quality, it is important to distinguish between a dataset producer's view (e.g., quality check and assurance of shared data) and user's view (e.g., information dealing with dataset fit-for-purpose, usability, and feedbacks from other users). For data quality, an important aspect to take into account is datasets maturity and applicability (i.e., which dataset is most useful for a specific application). A maturity model and matrix for climate data records have been proposed to ensure that basic measurements (e.g., raw data) are consistently transformed in quality-controlled, homogenized, and meaningful products (Bates and Privette, 2012). This model has been further developed by the EU FP7 project COordinating earth observation data validation for RE-analysis for CLIMAte Services (CORE-CLIMAX[45]). The matrix gives information about how mature a dataset is in terms of metadata, quality, software, usage, documentation, uncertainty, and accessibility (EUMETSAT, 2014).

To tackle the issue of uncertainty in the Earth Observation domain, the EU recently funded several programs. UncertWeb (http://www.uncertweb.org) and GeoViQua (http://www.geoviqua.org) projects have introduced instruments (i.e., frameworks, models and tools) to propose an interoperable representation of data uncertainties and quality. In particular, the Uncertainty Markup Language[46] (UncertML) and the Quality ML[47] are conceptual models and XML encoding designed to quantify, describe and exchange data quality and uncertainties (Diaz et al., 2012; Pebesma et al., 2011; Zabala et al., 2013). The OGC "NetCDF Uncertainty Conventions" (NetCDF-U) makes use of UncertML to formalize datasets uncertainty in a netCDF file (Bigagli and Nativi, 2013). In the framework of the EarthCube programme, the USA NSF has funded the "Advancing netCDF-CF for the Geoscience Community" project[48] which has been discussing on advanced CF conventions to document quality and uncertainty characterizing netCDF-CF datasets. GEOSS recently introduced a set of Data Management Principles[49] as a guideline for data providers to advance the quality of shared datasets. Among others, the EU funded projects Gap Analysis for Integrated Atmospheric ECV CLImate Monitoring (GAIA-CLIM[50]), Fidelity and uncertainty in climate data records from Earth Observations (FIDUCEO[51]), and Quality Assurance for Essential Climate Variables (QA4ECV[52]) (Scanlon et al., 2015) are tackling the aspect of uncertainty of EO-based climate data.

Finally, concerning models and projections, various methods are used to visualize uncertainty data. However, most of them are not supported in a standardized and consistent approach (Blower et al., 2015; Kristin et al., 2009). In particular, regarding model ensembles, UncertML and NetCDF-U appear interesting solutions as exemplified by the work done by ECMWF in the frame of the UncertWeb project[53] to represent probability distributions.

5.4. Coping with data visualization and download

Data visualization is an important tool for both scientists and non-scientists. It allows understanding and handling large volume of environmental data and for communicating scientific results within, between and outside scientific communities (Blower et al., 2009; Harold et al., 2016). Various techniques exist to visualize climate and environmental data (Kaye et al., 2012; Nocke et al., 2008; Sun et al., 2012). Typical limitations identified by these authors are lack of interactivity, lack of transparency, and lack of interoperability. Moreover, the heterogeneity of climate data (e.g., spatial, temporal, multi-variate, gridded, station measurements, remote measurements) requires different visualization techniques (e.g., 2D-maps, 3D-globes, time-series graphs) (Nocke et al., 2008).

To facilitate the visualization and access of climate data to different users' audience, current standards can greatly help in building standard-based, interactive, interoperable, web-based visualization systems of four-dimensional climate data (Sun et al., 2012). The OGC Web Map Service (WMS) is a mature standard for serving graphical representation (images) of geospatial data (Open Geospatial Consortium, 2006a). This standard supports multi-dimensional representation of complex data (e.g., time, elevation). A data-publishing server like GeoServer can easily handle the publication of netCDF data and expose it as WMS service[54]. This enables any client that implements this standard to interactively visualize raster (e.g., satellite images), vector (e.g., geospatial 2 D data such as a point, line or polygon), and multi-dimensional data (e.g., netCDF). Other solutions like THREDDS that has the

[43] http://www.unidata.ucar.edu/software/thredds/current/tds/.
[44] http://charme.org.uk.
[45] http://www.coreclimax.eu.
[46] http://www.uncertml.org.
[47] http://qualityml.geoviqua.org.
[48] https://www.earthcube.org/group/advancing-netcdf-cf.
[49] https://www.earthobservations.org/documents/dswg/201504_data_management_principles_long_final.pdf.
[50] http://www.gaia-clim.eu.
[51] http://www.fiduceo.eu.
[52] http://www.qa4ecv.eu.
[53] http://www.uncertweb.org/uploads/deliverables/e790f9107ac313083b15cbf91f90a7aa0c8fa3ac.pdf.
[54] http://geoserver.geo-solutions.it/multidim/en/index.html.

GODIVA2 viewer is also able to publish and handle WMS (Blower et al., 2009). The proposed WMS-Q standard (http://www.geoviqua.org/WMS-Q.htm) adds quality and uncertainty information (Blower et al., 2015) and visualize them with clients like Greenland[55], ncWMS-Q or MiraMon[56].

Concerning station measurements that are usually providing access to point-measurement time-series, the OGC Sensor Observation Service (SOS) is of high interest (Laney et al., 2015). It also enables users to integrate this type of climate data in an interoperable web-based framework.

To access data, the Web Feature Service (WFS) and the Web Coverage Service (WCS) enable users to download 2D georeferenced data (Open Geospatial Consortium, 2006b; 2010b).

OPeNDAP[57] is a popular standard technology (i.e. data model, software client and server components) in the oceanography community, to access climate and forecast datasets. It is based on the DAP2 protocol[58], which provides a discipline-neutral means of requesting and providing data across the Web-in particular, DAP2 provides a constraint notation for requesting parts of a multidimensional dataset.

Finally, to visualize statistics, the OGC Table Joining Service (TJS) is a standard that defines how to join tabular data (i.e., statistics) with a spatial reference (Open Geospatial Consortium, 2010a). This standard can help linking socio-economic and environmental data together (Grothe and Brentjens, 2013).

5.5. Improving data processing

Computing and IT infrastructures have been identified has a critical element to build the GFCS to facilitate data flow, transformation, analysis and processing of the exploding volume of climate data (Street, 2015). Different types of climate data sources (e.g., sensors, satellites, models) are required to develop and apply advanced data processing algorithms to describe the temporal evolution of climate. Moreover, the increasing volume of climate data generated at increasingly finer spatial and temporal resolution has made it necessary to use computing power that exceed the current capacities of single computers (Overpeck et al., 2011).

To tackle the issue of processing algorithms sharing and computing power, the OGC Web Processing Service (WPS) (Open Geospatial Consortium, 2007b) and the High-Performance and Distributed Computing paradigm (Buyya et al., 2009) can help.

WPS is a standard specification providing rules on how to invoke inputs and outputs as standardized web-based processing service. It defines how a client can request the execution of a process; how a provider can publish a processing algorithm as a service; and how the output of a process is handled. This enables providers and users to share algorithms in an interoperable way. However, to turn climate data into understandable information, efficient processing solutions are required. Distributed high performance computing infrastructures such a Super Computers, Clusters, Grids, and Clouds appear as promising solutions (Bosin et al., 2011; Shujia et al., 2010). Efforts are underway to unleash the power of computing infrastructures through interoperable web-based processing services (Giuliani et al., 2012; Mazzetti et al., 2016; Rodila and Gorgan, 2012; Rodila et al., 2015). The objective of such integration is to enable efficient analysis in a transparent and interoperable way, hiding the complexity of the infrastructure while letting users concentrating on analyses. WPS can play an important role also in the future distributed processing and analytics frameworks by supporting relevant patterns such as the Model-as-a-Service and the Online Analytical Processing (OLAP) interfaces –see for example, the GEO Model Web (Nativi et al., 2013c) and the Data Cube infrastructure interfaces (Gray et al., 1995).

5.6. Facilitating integration and multi-disciplinarity

Another challenge to enhance the quality and relevance of climate data rests in the integration and framing of climate data with other sources to support decision-making (European Commission, 2015; Street, 2015). Decisions related to the climate require the integration of multiple sets of complex information about physical, chemical, biological, and socio-economical systems often provided by different organizations. Moreover, climate data can be useful for other scientific (and non-scientific) communities of practice. This raises the necessity of a collaborative, multi-disciplinary, and multi-stakeholder effort to provide an integrated access to climate resources. To support this effort it is necessary to find a consensus and ensure a given level of harmonization, while recognizing the diversity of stakeholders (both datasets providers and users) with their different aspirations and mandates (Strobl et al., 2011). Probably the best attempt to build a multi-disciplinary framework based on existing systems is represented by the System of Systems engineering approach exemplified by GEOSS (Béjar et al., 2009; Nativi et al., 2013b). GEOSS recognizes the heterogeneity of systems that reflect the diversity of stakeholders and decided not to impose a common and limited set of specifications to the different providers and users. Instead, GEOSS aims to act as a broker between data providers and users (Nativi et al., 2012, 2013a, 2015). Indeed, in the Earth science community there are different interoperability interfaces, tools and standards, thus making it very difficult to build a multi-disciplinary framework for non-experts. To address these issues, GEOSS has developed a brokering framework enabling the binding of heterogeneous resources published by different data providers. The brokering framework implements all the mediation and adaptation tasks necessary to map the different standards, used by the heterogeneous communities, onto a common harmonized interface, which is completely transparent for both the data providers and users.

This facilitates linkages between communities allowing them to search, discover, and access heterogeneous resources, while allowing data users and providers to continue using their tools and publishing their resources with their usual standards. Such a framework can facilitate commitment, endorsement and acceptance on interoperability and creating the basis for a multi-disciplinary and integrative research. This fit very well with the needs of climate policy that requires a suitable science-policy interface to ensure that the best climate science is adequately transferred to decision-makers or other users. Finally, such an integrative framework can also facilitate interconnection/coupling of models as demonstrated by GEO Model Web initiative (Nativi et al., 2013a,b,c) that helped to link Climate Change and Biodiversity infrastructures (Nativi et al., 2009) or by the Open Modeling Interface (OpenMI) (Castronova et al., 2013; Goodall et al., 2013; Laniak et al., 2013).

5.7. Develop tailored applications and products

Once data and metadata are published and accessible through interoperable web services, it greatly facilitates the development of tailored applications that can answer users' needs. For example, web-based frameworks such as D3JS (https://d3js.org) enables manipulating documents based on data combining powerful visualization techniques and a data-driven approach. Depending on users' requirements, it allows generating different dynamic and interactive views (e.g., in the form of graphs or maps) of a same dataset. With such frameworks, applications are usable on both desktop and mobile devices. They also allow the development of dashboards than can be defined as a readable, intuitive, and interactive user interface showing a graphical presentation as a graph and/or a map of the current status and trends of a variable or indicator to enable immediate and informed decisions to

[55] https://wiki.52north.org/bin/view/Geostatistics/Greenland.
[56] http://www.creaf.uab.es/miramon/Index_usa.htm.
[57] https://www.opendap.org/about.
[58] https://www.opendap.org/pdf/dap_2_data_model.pdf.

be made. Dashboards can be a powerful tool to monitor ECVs or other climate-related datasets and to track their evolution through time. These kinds of products can certainly help to raise the value of climate data and services as well as reducing the gap between scientists and decision-makers.

5.8. Developing capacities and enhancing data policies

One of the objectives of the GFCS is to facilitate the development of the market for climate services that deliver social and economic benefits at various scales (Street, 2015). To support this objective, the GFCS encourage global, free and open exchange of climate-relevant data. Currently, there are several ongoing open data policies for facilitating the access and use of public data like the Digital Agenda for Europe. Such policies can support a more effective and immediate translation of data into information by building interoperable user-driven services (Cuca, 2016). It is essential to realize the value that open data can have on economy (e.g., broad benefits and growth), on society (e.g., enhanced social welfare), on research and innovation (e.g., new types of research, reproducibility, accountability), on education, and on governance (e.g., transparency) by encouraging the use and uptake of data (CODATA, 2015; Ryan, 2016). It can increase the use of - as well as bring important returns on - investment, potentially of several orders of magnitude higher than the initial investment. Probably, one of the best examples of the success of a broad and open access policy is the NASA Landsat program (National Geospatial Advisory Committee – Landsat Advisory Group, 2014). In 2008, the US government decided to completely open up the Landsat archive. Prior to this data, Landsat were sold at a price ranging between $500–$5000. At the peak of data sales in 2001, a mean of 52 scenes per day were sold corresponding to a revenue of $4.5–5 million. Immediately after the open data policy, data access increased to a mean of 5700 scenes per day for a revenue estimated in 2011 to around $2 billion (Ryan, 2016). Such policies can help to develop value-added products and services, increase transparency, and offer promising business opportunities and help national economies. From a scientific perspective, if such policies are adopted globally, it will completely transform our understanding how the Earth System works facilitating large scale access and integration of terrestrial, oceanic, and atmospheric data provided by government agencies.

However, to fully realize the potential of open data policies together with interoperable access to data, a key enabler is to develop capacities at human, institutional, and technical levels. It helps to raise awareness and create commitments on the benefits of data sharing and publication with interoperable solutions. Integrated material such as the “Bringing GEOSS services into practice”[59] (Giuliani et al., 2016b) can help to lower the entry barriers for both data providers and users, facilitates the development of technical skills, and empowers people.

6. Selected examples of increased use of interoperability in climate science

Several projects and initiatives are embracing interoperability in climate science and thus contributing to build spatially-enabled climate services. This contributes to a gradual shift towards more open, inclusive and interoperable systems, increasing the climate-data value chain and closing the gap between data providers and users. A good example is the C-READ platform[60] of the Caribbean Community Climate Change Center. It leverages several open standards components to provide interoperable discovery, access, processing functionalities for the monitoring of climate and environmental changes in the Caribbean region, allowing different partner countries and organizations to combine their data together with historical data to provide value-added information products to inform decision and policy makers. Härtwig and Müller (2013) demonstrated how to use interoperable access to data together with processing services to provide climate classification functionality. It helps to give an intuitive overview of the distribution of different climate conditions around the globe. Sun et al. (2012) used Google Earth to develop a web-based visualization for climate research. For these authors, the use of an interoperable solution increased significantly the awareness, usability and visibility of scientific results. Sweden and UK have also implemented several open standards to increase the reuse of scientific environmental and climate data (Klein et al., 2013; Stephens et al., 2012). They highlight the importance of scientific data sharing as a prerequisite for new scientific findings, knowledge, and services, supporting decision-making to the rapid environmental and socio-economic challenges. Woolf et al. (2006) have demonstrated how interoperability standards can support the publication of legacy data sources, thereby highlighting the benefits for enabling simple use of data with deprecated data formats. Bernard and Ostländer (2008) have demonstrated how beneficial standards can be to assess vulnerability to climate change. Other interesting examples that can be mentioned are: the European Centre for Medium-Range Weather Forecasts (ECMWF[61]) that uses OGC WCS and WPS to offer interoperable services to access over 50 Petabytes of operational and research data (Wagemann et al., 2017). The Copernicus Atmosphere Monitoring Service[62] enables users to discover high volume of data related to atmosphere composition. The United Nations Environment Programme (UNEP) has used the brokering technology to developed interactive graphs that allow monitoring the evolution of a set of ECVs in real-time[63]. Another nice example of a platform that make extensive use of interoperability arrangement to facilitate data discovery, access, process, and visualization of Europe’s climate data and information, is the EU project Climate Information Portal (CLIPC[64]). Finally the Climate Inspector[65] enables users to investigate climate change around the globe across space and time, looking at climate trends, variability and uncertainty and access maps and data (Inman, 2011; Wilhelmi et al., 2016).

All these examples emphasize that interoperability provides climate services that are more efficient, enhances data integration, as well as the development of tailored products and services. These systems enable developing synergies and improving communication between scientists, stakeholders and decision makers, greatly advancing climate data sharing and scientific research collaboration.

7. Discussion and perspectives

During the COP21, countries were invited to adopt the Open Data Charter[66] to open climate data for enhancing a collective action exemplified by *“Data for Climate Action – a global open innovation initiative for climate resilience”*[67]. Similarly, the WMO Resolution 60 on data policies for climate data in support of the GFCS that was endorsed in 2015 is also calling for open sharing of climate data (World Meteorlogical Organization, 2015). This charter is based on the following principles: (1) open by default; (2) timely and comprehensive; (3) accessible and usable; (4) comparable and interoperable; (5) for improved governance and citizen engagement; (6) for inclusive development and innovation. Several contributions have emphasized the need for open sharing of quality-assured data and services underlying published scientific knowledge to support climate change research and policymaking (Kaye et al., 2012; Nocke et al., 2008; Otto et al., 2015; Overpeck et al., 2011;

[59] http://www.geossintopractice.org.
[60] http://c-read.net.
[61] http://www.ecmwf.int.
[62] http://atmosphere.copernicus.eu.
[63] http://ede.grid.unep.ch/extras/graphs_list.php.
[64] http://www.clipc.eu.
[65] https://gisclimatechange.ucar.edu/inspector.
[66] http://opendatacharter.net.
[67] http://www.unglobalpulse.org/data-for-climate-action.

Sessa and Latham, 2008; Street, 2015). Particularly, scientists developing climate services should work in close connection with decision makers to deliver services corresponding to their needs. From a technical perspective, interoperability is a key enabler to facilitate the access to climate data and information in an efficient way.

7.1. Benefits

The major benefit of spatially-enabling climate services is that it brings interoperability along the entire data value chain. It facilitates storing, visualizing, accessing, processing/analyzing, and integrating climate data and information and enables users to add create value-added products and services. NetCDF-CF, likely the most common data format in climate science, is already an OGC standards (Domenico and Nativi, 2012) and most of data publication tools (e.g., GeoServer, TDS) supports netCDF data. Therefore, it is simple to publish these data through interoperable web services.

Within Climate Science community netCDF is recognized as a de facto standard for array-oriented scientific data. However, a data model that is tailored to the needs of one discipline may not be appropriate for sharing data to other disciplines (Nativi and Domenico, 2009). Consequently, netCDF file based sharing might not be the best solution, while spatial databases can provide more flexibility. Indeed, time series and especially real-time data are difficult to store in existing SDIs (Härtwig and Müller, 2013). While for data with no or low update frequency (e.g., land cover) the best way to store is in spatial databases like PostGIS, time-series measurements (e.g., precipitation) are mainly stored in netCDF files. From a user point of view, it would be much easier to have a custom spatio-temporal subset of the climate data extracted from a spatial database and to be downloaded in different formats. To tackle this issue and provide more flexibility, the OGC SOS standard is particularly suited. It allows storing time-series measurements in a spatial database; facilitate integration with other data types through a standardized interface; and enables data extraction (e.g., by geographical and/or temporal extent) in various formats. Such approach has been exemplified in flood protection (Cannata et al., 2015), ecological observations (Munoz et al., 2014), water quality monitoring (Horsburgh et al., 2010), air quality monitoring (Stasch et al., 2012). All these examples have shown an increased interoperability, usage, and facility to integrate time-series measurements with other data. Experiences to use the SOS standard for providing gridded climate data to agricultural applications (Chinnachodteeranun and Honda, 2016) and for climate modeling (Kutschera et al., 2011) have shown similar benefits.

Delivering climate services using interoperable web services can lower the barriers for both data providers and data users. In particular, it can enhance the reusability of data and components in various applications, and get increased return on investment. For example, the WPS standard can help deliver services as simple as generating maps or graphs up to execution complex climate models on super computers. Another example is to help publishing legacy data. These data can be very useful to deliver time-series information but due to the fact that they are in formats that are outdated they are not used. By publishing these data with interoperable services, they are thus instantly available to all software, tools, and applications that have implemented such standards. It can then leverage the information power of these data. Finally, using standardized web services enable coupling models more easily (like coupling climate and hydrological models (Goodall et al., 2013)) and contributing to develop Earth System Models such as Earth System Modeling Framework (ESMF) (Collins et al., 2005; Hill et al., 2004), the GEO Model Web initiative (Nativi et al., 2013a,b,c), or Environmental Virtual Observatories (EVO) (Karpouzoglou et al., 2016).

From a scientific perspective, it can help increase the integrity of data underlying climate research. During the Climategate (i.e., illegally hacked emails from the University of East Anglia in November 2009 claiming that global warming was just a conspiracy), several scientific studies have reported the difficulty to reproduce research results because of missing or poor quality datasets (Brahic, 2010; Garud et al., 2014; Skrydstrup, 2013). Interoperable climate services together with corresponding technical and scientific capacities can play a crucial role in ensuring quality, integrity and availability of datasets and consequently promoting, contributing and supporting research activities and a trusted open science.

Finally, using interoperable services can answer challenges identified by several authors. It brings interactivity and facilitate climate data visualization (Nocke et al., 2008), it facilitates integration to determine the value of an ecosystem (Hungate and Hampton, 2012), explores how biodiversity evolves with a changing climate (Stefano Nativi et al., 2009), uses EO data for monitoring ECVs (Obregón et al., 2014), or publishes in-situ measurements using Sensor Web Enablement (SWE) suite of standards.

7.2. Challenges

Even if interoperability can lead to numerous promising benefits for spatially-enabling climate services, there are also a number of challenges to be addressed. Among them, we can mention: (1) data visualization; (2) data volume; (3) data dimensions (e.g., time and space); (4) capacity building; (5) institutional and policies (Bojinski et al., 2014; Härtwig and Müller, 2013; Nocke et al., 2008; Woolf et al., 2005).

Data visualization is an essential technology for presentation and communicating climate data. However, due the variety and complexity of climate data (e.g., mutli-dimensional, space and time) it is a challenging task. In particular, visualizing data quality and uncertainty is key as it can affect policy design (Otto et al., 2015). WMS-Q, QualityML and UncertML can be the basis for a standardized and interoperable visualization approach of uncertainty and quality of climate data.

Another challenge relates with the enormous volume of climate and the complexity of climate models that require efficient and powerful processing capacities. Clearly, climate data are part of the Big Data paradigm and new approaches for processing climate data are required. Distributed computing and code mobility are promising solutions to solve this issue (Nativi et al., 2015).

From an interoperability perspective, syntactical and structural are important steps towards full interoperability. However, effective data use requires semantic interoperability, which is still a major issue to tackle. Semantic interoperability enables systems to link external resources through standard reference mechanisms (see Linked Data), giving them the ability to exchange data with unambiguous shared meaning, enabling machine logic, inferring and knowledge generation (Hitzler and Janowicz, 2013; Kuhn et al., 2014; Schade et al., 2011).

Besides technical aspects, an important challenge relies on governance, policies, and institution. In term of governance, the GFCS is already in place and GEO and GFCS have identified mutual benefits and are currently making efforts to strengthen their cooperation. This emphasized by a recent joint activity of the GEO Work Programme that is aiming to improve the coordination between GEO and the GFCS to build linkages at the national and regional level between activities implemented under both frameworks and support the five GFCS priority areas[68]. This can certainly help to reach commitment and get support to bring interoperability on the table. Open Data policies and Data Sharing Principles are spreading in various communities and this will strongly influence climate community as well as institutions that are providing data and delivering climate services.

Finally, an important challenge concerns the development of capacities at human, institutional, and infrastructure levels (Giuliani et al., 2013). Building capacities will help to reach large adoption, acceptation and commitment on data sharing principles. It will also strengthen the capacity of scientists to provide usable and understandable

[68] https://www.earthobservations.org/activity.php?id=95.

information to decision makers and convince data holders to make available their data to a wide audience facilitating data discovery, access, and processing.

7.3. Perspectives and recommendations

Unlike the notion of Ecosystem Services (e.g., the benefits people obtain from ecosystems) the definition of Climate Services mostly concentrate on informative aspects to ensure that reliable climate science is effectively communicated to end-users. This terminology can be confusing because people also obtain benefits from climate, since it influences all aspects of human societies in a variety of ways. Climate data and information play an essential role for national development planning, managing risks and developing efficient mitigation and adaptation strategies. This requires that climate data and information can be integrated into various applications as well as policies.

Considering the importance of climate data, starting to enable an interoperable access to all ECVs appears to be crucial. All the data sources have been already identified by GCOS and they have been recognized as essential to support the work of IPCC and UNFCCC. Providing an interoperable access to these key data will certainly help the GFCS to gain further commitments and support. This can be done together with the Group on Earth Observations that is building GEOSS, dealing with Climate as a cross-cutting area of overarching importance giving discovery and access capabilities to various climate data[69]. Moreover, with the brokering framework develop within GEOSS, it should be easy to engage the major ECV data providers and enable an interoperable access. Using the brokering approach will ease integration and facilitate multi-disciplinary approaches. This is even more important in the light of the ongoing global sustainability efforts such as the 2030 Global Agenda on Sustainable Development setting up Sustainable Development Goals (Brandi, 2015; Griggs et al., 2013; Lu et al., 2015); Planetary Boundaries (Rockstrom et al., 2009; Steffen et al., 2015); Nexus (de Strasser et al., 2016); or Natural Capital (Costanza et al., 1997; Guerry et al., 2015) approaches. In all these efforts, climate data and information are an essential component and consequently having interoperable climate services will greatly facilitate integration. The OGC has released a White paper[70] on *"OGC Information Technology Standards for Sustainable Development"* showing that OGC standards can be highly beneficial for enhancing data value chain related to these sustainability efforts. It is also a first step from data towards knowledge. Indeed, data and information are not sufficient to take good decisions (Ackoff, 1999; Rowley, 2007). Interoperability can help to build efficient data value chain, supporting most of the GFCS objectives previously mentioned. It can also facilitate providers and users to engage in delivering climate services and ultimately accelerate innovation (Brooks, 2013). In particular, it can help developing countries to access data and information that are not available, access computing and processing capabilities that they cannot afford (e.g., shared infrastructures, cloud computing), and facilitate the access to internet in low bandwidth conditions (e.g., dedicated data formats like Geopackage) (Rashidan and Musliman, 2015; Singh and Bermudez, 2013). Finally, interoperability can increase integrity, transparency, and foster collaboration. These are at the heart of the GFCS Ethical Framework for Climate Services[71].

8. Conclusions

Addressing the challenges of climate change is critical for a more sustainable future. The Global Framework for Climate Services represents a global coordinated effort to improve the welfare of people vulnerable to climate variability and climate change.

Providing climate information that responds to users' needs and assists individuals and organizations in making decisions requires effective and efficient mechanisms. In particular, it should be coordinated in a coherent chain to create and build value. Climate data and information are essential to understand major environmental changes. It is crucial to make these data and information available not in the way that it is collected, but in the way that it is being used by the largest audience possible. Therefore, being able to easily combine climate data with other data sources is a major prerequisite to enable multi-disciplinary scientific analysis on the environment.

To deliver efficient climate services, interoperability is an essential element to consider extending the notion of service to provide a technical perspective as well. The GFCS should extend efforts towards more interoperable and web-based services. To answer this need, many open geospatial standards already exist and can be beneficial to strengthen the climate community to deliver interoperable climate services. These standards can be useful all along the data value chain (e.g., from data acquisition to decision-making) and can greatly enhance the scope of climate services. Enabling an interoperable access to all 50 Essential Climate Variables can help leveraging the full potential of climate services and can significantly contribute to the advancement of GFCS objectives and vision. Interoperable climate services have the potential to become the intelligence towards the transition to a climate-resilient society. They can support decision-makers taking informed decisions based on the best scientific knowledge to improve resilience, adaptation and mitigation strategies. Finally, thanks to interoperability, it can broaden the scope of climate services allowing to easily bring data into frameworks such as SDGs, Nexus, Natural Capitals, or Planetary Boundaries.

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