KEPLER Deliverable Report

Report on Deliverable D3.1

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Lead author	Jeremy Wilkinson, UKRI-BAS			

Contributing authors

- **UKRI-BAS**: Jeremy Wilkinson
- **Lund**: Margareta Johansson
- **AWI:** Astrid Bracher
- **Met.No:** Penny Wagner, Nick Hughes
- **NERSC:** Annette Samuelsen

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Executive summary

In the 2017 Briefing Paper[1] entitled *'Securing the Copernicus programme: Why EU earth observation matters'* the Copernicus programme was described as a user-driven programme which provides six free-of-charge operational services (atmosphere monitoring, marine environment monitoring, land monitoring, climate change, emergency management and security) to EU, national, and regional institutions, as well as to the private sector. They went on to mention that the Copernicus programme is organised in three components, a space component, an *in situ* component and a service component. The *in situ* component is aimed at ensuring coordinated access to observations from airborne, seaborne, and ground-based installations. As a result, *in situ* observations must play an important part within the Copernicus Services. With this in mind, Deliverable 3.1 has two aims:

1. To investigate the role citizen science can play in the expansion of Copernicus' *in situ* monitoring priorities.
2. To assess how the observational research community, both marine and terrestrial, can better contribute with *in situ* monitoring to the aims of Copernicus Services.

During the process of addressing these aims it became clear that there was a lack of (i) dialogue between the Copernicus Services and citizen science projects; and (ii) engagement by the Copernicus Services with the major European Polar bodies (such as the European Polar Board) including EU-funded programmes (such as EU-PolarNet and the Horizon 2020 funded projects of the EU Polar Cluster). For example, the EU funded INTERACT programme has a vast network of terrestrial research stations spanning the entire Arctic. These assets have great potential to become a ground validation and calibration network for Copernicus products and services but within our consultation process we found a lack of interaction or cooperation between the INTERACT's network of Arctic research stations and the Copernicus Services.

The analysis of the QUIDs (QUality Information Documents) for some of Copernicus' polar products reveals that the lack of temporal and spatial *in situ* data in the polar regions is causing real problems in assessing the quality of these products, as well as severely compromising calibration and validation activities. The evidence gathered in this report suggests that citizen science and the European polar research community are presently underutilised by the Copernicus' Services. If given the opportunity, we believe they can make a welcome contribution to enhancing the relevance of the Copernicus Services to European citizens, as well as helping to evaluate and improve the accuracy of Copernicus products themselves.

Our document is divided into two parts; Part 1 looks at Copernicus and the role citizen science projects can play in improving Copernicus polar products. Part 2 investigates the role the European polar research community (that is involved in in situ measurements) presently plays in Copernicus. At the end of each Part we provide suggestions on how to improve Copernicus' use of *in situ* observations. A selection of our suggestions include:

- Prioritising Cal/Val *in situ* measurements in the polar regions. This is desperately needed to reduce the large uncertainties that have been identified within QUIDs that describe Copernicus products

[1] https://www.europarl.europa.eu/RegData/etudes/BRIE/2017/599407/EPRS_BRI%282017%29599407_EN.pdf

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- Making a greater effort to highlight and grow the number of Citizen Science projects using Copernicus products or validating their products. In particular, Copernicus should prioritise the development of mechanisms to encourage, support and facilitate more Citizen Science projects to be involved in the Calibration and Validation (Cal/Val) of the present and future Copernicus products and services.
- Developing a clear framework whereby Copernicus Services can better utilise European polar research assets (i.e. stations, ships, aircraft and people) to provide regular Cal/Val opportunities for Copernicus products.
- Enhancing opportunities for the broader European polar community to develop closer relationships with the Copernicus Services.
- The Copernicus In Situ Component is currently under-utilised, and could play a stronger role in providing a more independent quality control to Copernicus Services and their products.

Furthermore, within this report we provide an overview of recommendations from other programmes that also reviewed similar topic areas. Acknowledging, reviewing and addressing all these suggestions should provide a pathway for Copernicus Services to incorporate more *in situ* data, which in turn should lead to more accurate products, enhance the uptake of these products, and improve both monitoring and forecasting capabilities in the Polar Regions.

Part 1. Citizen science

The participation of non-specialists in scientific research, i.e. the public, is generally referred to as Citizen Science, Community-Based Observing, Public Participation in Scientific Research, Volunteered Geographic Information, or Crowdsourcing. In this report, we will use the term Citizen Science (CS), which we define as being:

> ***"Voluntary collaborations in scientific research that is conducted, in whole or in part, by non-professional scientists, whose outcomes both advances scientific knowledge, and increases the public's understanding of science."***

Whilst the name CS is becoming more well used, it is not as commonly known as one would think, a recent survey found that less than half of respondents were familiar with the term CS, but over 70% were familiar with the concept by another name (Lewandowski, E., et al 2017). This suggests there is a need for a consensus regarding nomenclature/ terminology. Even so, it is fair to say that CS has been a welcome addition to many, if not all, scientific disciplines.

It is well documented that the participation of non-specialists in scientific research has yielded important contributions to both the advancement of science and the public understanding of science.

CS is now seen as a legitimate way of broadening and involving a wide variety of people in different scientific endeavours. Voluntary participation between scientists and the public is undergoing a revival, so how can CS work to enhance the Copernicus Services and the uptake of their Arctic products?

The aim of this section of the report is to provide an overview of what CS projects are, and what is needed for a CS project to be successful within their stakeholder groups. From this we will attempt to better understand the role CS programmes can **play in the expansion of Copernicus'** *in situ* monitoring priorities, and in particular we will provide a series of suggestion so that Copernicus Services can be better linked into CS programmes. To do this we provide the following chapters:

- Chapter 1: Overview of citizen science (CS)
- Chapter 2: CS success stories, what are the successful ingredients?
- Chapter 3: Options to enable CS to better interact and enhance the use of *in situ* observations in the Copernicus Services

For information regarding Community-Based Observing and Societal Needs regarding Indigenous and local Arctic community priorities, the reader is referred to KEPLER deliverable D1.4 Overall Assessment of Stakeholder Needs.

Chapter 1: Overview of citizen science (CS)

Performing Arctic scientific research can be difficult, expensive, and as the scientists generally do not live locally, it can be time-consuming to get to and from the field sites. As a result, *in situ* measurements in the Arctic are spatially and temporally sparse. About 4 million people live in the Arctic, and every year there is a significant increase in visitors to this area. Taking advantage of this exceptional knowledge-base, through the co-production of knowledge via CS, without compromising scientific rigor, is a great opportunity to help advance both scientific knowledge and engagement.

Empirical studies of field-based CS programmes have shown that participation in CS increases scientific literacy, the promotion of knowledge, and the understanding of scientific concepts and processes (Aristeidou and Herodotou 2020). A better understanding of the scientific process is one of the fundamental benefits of any CS project. But perhaps it is what CS brings to a project that is most noteworthy, the research can benefit from their many unique perspectives, skill sets, and knowledge as well as identifying a research topic or disseminating results (Lewandowski. et al. 2017). In the field of ecology, for example, CS has been a huge success; the amount of additional data being generated from observations performed by non-scientists is truly staggering. CS programmes have recorded hundreds of millions of individual observations, extending immensely what could be achieved by scientists alone. (Miller-Rushing et al. 2019). It should be remembered that Ecology is only a small section of CS activities. The visibility of the Copernicus Services to the average European citizen would increase incredibly if their products were regularly utilised within CS projects. Moreover, envisage the benefit to science if the power of CS could be applied to the validation and/or calibration of the Arctic products delivered by Copernicus Services or ESA.

See et al., (2016), provides several successful examples of where CS has led to new scientific discoveries such as new knowledge about protein structures, discovering new galaxies, websites for public reporting of illegal logging/deforestation, illegal waste dumping and more. It is important to remember that CS has an impact that extends beyond the advancement of scientific knowledge. CS findings can be used to change management strategies and provide scientific evidence for better decision-making and policy formation (Armitage et al. 2009). The source of scientific knowledge can influence how members of the public trust and interpret that knowledge (Jenkins 1999). When performed, CS can have a demonstrable impact upon our knowledge, lifestyle, and the environment, as well as local, regional and global governance.

Estimates by Theobald et al. (2015) suggest that in the field of biodiversity there are 1.3-2.3 million citizen scientists participating annually in CS projects around the world, providing an in-kind economic contribution value of up to €2.12 billion ($2.5 billion). CS covers a vast array of topics, geographic regions and demographics, but they generally fall within into five broad themes (Shirk et al. 2012):

1. ***Contractual projects,*** where communities ask professional researchers to conduct a specific scientific investigation and report on the results;
2. ***Contributory projects,*** which are generally designed by scientists and for which members of the public primarily contribute data;
3. ***Collaborative projects,*** which are generally designed by scientists and for which members of the public contribute data, but have a more of a stake in the project by helping to refine project design, analyse data, and/or disseminate findings;

4. ***Co-Created projects,*** which are designed by scientists and members of the public working together and for which at least some of the public participants are actively involved in most or all aspects of the research process; and
5. ***Collegial contributions***, where non-credentialed individuals conduct research independently with varying degrees of expected recognition by institutionalized science and/or professionals.

Each of these five themes has their strengths and weaknesses, however, given the definition of CS we presented at the start of this report, we suggest the middle three themes are most suitable (2. *Contributory projects, 3. Collaborative projects and 4. Co-Created*) projects fit the CS vision better. Surveys have shown that people were more confident in hypothetical CS findings when professional scientists were involved to some degree, compared to situations in which only citizen scientists were involved (Lewandowski et al. 2017). This reinforces the need for co-production and co-design of CS projects between scientists and the public. However, it is Theme 3 *Co-Created projects* that seem to best embody the goals and expectations of both scientists and the public through co-production and co-development of a CS programme. Interestingly, Shirk et al (2012) point out that innovation often occurs at boundaries between these CS themes.

A crucial component of creating and maintaining a CS project is the recruitment of the public, as well as establishing an explicit feedback loop, where those collecting data, understand how their valuable efforts contribute to the science. Recruitment strategies have been linked to the approach of data gathering within CS projects, such as expanding data collection into areas that more closely match volunteer motivations to project experiences (Lewandowski and Specht 2015). What drives scientists and citizens to collaborate are varied, but to be successful, CS projects must address the needs and interests of all parties.

Studies have shown that the motivation of individuals to perform CS differ across communities and different demographic groups. One the overriding factors are the connection to place matters, especially in the field of biodiversity and conversation, level of interaction between professional researchers and citizens, and enhancing the link between the information that citizen scientists collect with on-the-ground evidence-decision making for better outcomes (McGreavy, et al. 2017). Depending on the nature of the project and participation, Pettibone et al., 2016, suggested benefits can be achieved for Science, Society and Participants (see Table 1 for a summary).

Benefits for Science	Benefits for Society	Benefits for Participants
• Inspires new research topics by inviting new ideas, questions, methods, and societal knowledge • Creates large datasets (spatially and temporally) that can be adapted to various uses • Allows diverse evaluation capacities including photos, scans and video sequences • Increases public acceptance of research results • Promotes public evaluation of research • Verifies the practical relevance and applicability of scientific results	• Generates and communicates socially relevant research topics • Allows co-creation of transparent research • Allows society to take on responsibility for research • Introduces all participants to new perspectives • Develops opportunities for societal transformation, e.g. towards sustainability • Promotes better transfer of research results into practice through early involvement of societal actors • Democratizes the discursive meaning of science • Strengthens civil society and government agencies	• Allows contributions to scientific discoveries • Improves understanding of science and sometimes advances scientific qualifications • Increases understanding of complex problems • Introduces innovative ideas into science • Facilitates participation in political decision-making through scientific contributions • Contributes ideas and suggestions for alternatives • Allows critical examination of scientific results • Promotes a better environment and a better society • Is fun and promotes sharing

Table 1. This table shows the potential benefits that can be achieved for Science, Society and Participants within CS project (from Pettibone et al., 2016)

The proliferation of CS projects has been driven by increased access to technology. See et al., (2016), suggests the interconnectivity made possible by the internet, smart sensors, and GPS-enabled mobile devices are the main drivers and the growth of the Internet of Things (IoT) continues to expand the possibilities for CS-driven data gathering. The KEPLER Deliverable 1.2 Community-Based Observing and Societal Needs suggested that *'satellite services and user access have been partly connected with the proliferation of cellular services associated with GPS-enabled smartphones becoming available to "ordinary people" as well as authorities and specialists'*. Easy access to technology has two major advantages

1. Citizens have the resources at their fingertips for collecting and analysing information, and when acting collectively this is performed on a massive scale
2. Software developed to run on internet-connected devices means that it is easy to be involved in CS programmes, and it is easy to upload /download data.

Even though our ability to monitor the environment through better sensors and faster computers continues to improve people-power has a noteworthy advantage; the ability of large numbers of

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citizen scientists to collect large quantities of data across space and time far outstrips the capacity of professional scientists, therefore, there will be a role for CS for many years to come. This is especially pertinent in an era of climate change. CS programmes provide local, regional and global observations (at higher spatial and temporal resolution) in numerous fields of study, as well as extending the time-series of essential climate variables that are needed if we are to understand the changes that are occurring today, and how they will manifest themselves in the future.

The use of CS to provide direct observations of different topics of research is an area where Arctic scientists have not had the resources to develop mechanisms that could channel the willingness and interest of thousands of people to be able to participate in scientific projects.

Society, knowledge, well-being and the environment are the winners when scientists and the public work together. For this reason, we need to ensure the Arctic is fully represented in future CS projects.

Further reading

European level:

Green Paper for Citizen Science in Europe: available here:

https://ciencia-ciudadana.es//wp-content/uploads/2018/09/GreenPaperOnCitizenScience2013.pdf

National level:

Germany: Green Paper Citizen Science Strategy 2020 for Germany, available here:

https://www.buergerschaffenwissen.de/sites/default/files/assets/dokumente/gewiss_cs_strategy_englisch.pdf.

United States Public participation in scientific research: defining the field and assessing its potential for informal science education. A CAISE Inquiry Group Report. Center for Advancement of Informal Science Education (CAISE) is available here: https://files.eric.ed.gov/fulltext/ED519688.pdf

Other information:

- There are significant resources on how to conduct CS projects, a good starting point is resources compiled by http://www.citizenscience.org.
- The European Citizen Science Association (ECSA) is a non-profit association set up to encourage the growth of the Citizen Science movement in Europe to enhance the participation of the general public in scientific processes, mainly by initiating and supporting citizen science projects as well as performing research on citizen science. https://ecsa.citizen-science.net/

Chapter 2: CS success stories, what are the successful ingredients?

One of the more famous CS applications that had global reach, was the search for extraterrestrial intelligence (SETI). The SETI@home[2] project broke new ground as it was a scientific experiment which utilised the computer resources of millions of people's internet-connected computers to search for life beyond Earth. This project had over 5.2 million participants worldwide, and even though life was not detected it was a great success for community-based participation with a scientific endeavour.

In fact, the 21st century has seen an explosion of Citizen Science projects, and these projects are having a greater impact. For example, the SCI-STARTER web-site lists over 1,200 citizen science projects (April 2019), with other sites listing similar amounts of CS projects. An international organization, The Polar Citizen Science Collective (PCSC), was established in 2018 for CS activities, particularly aimed at the polar tourism industry. Tourism vessels can typically offer berths for scientists to conduct their data collection on the vessels accessing these remote areas, however, the PCSC acts as a conduit between CS and research, and instead allows passengers to participate in data collection. This inspires new ambassadors to these sensitive ecosystems and increases the uptake of valuable data for researchers. More recently, in June 2020, NASA released a statement saying a citizen scientist spotted a never-before-seen comet using data freely downloaded from the Solar and Heliospheric Observatory.

The Copernicus Services, with their open-access policy to satellite data and other spatial products, have given European citizens (and others) access to vast amounts of spatial data about our locality, region and planet. The combination of the commitment of the Copernicus Services to new technologies, the continuation of the collection of key datasets, and the easy online-access to these datasets (as well as historical datasets) suggest they are well-placed to enhance the CS experience. Given the benefits that flow when scientists and the public work together, the Copernicus Services, or the Copernicus In Situ Component, could act as a catalyst for CS Arctic-focused projects (or any CS project for that matter), which in turn will increase the visibility and uptake of Arctic-relevant Copernicus products. But what are the ingredients needed for CS success?

The growing creativity and broad appeal of CS make it nearly impossible to predict what will be the next big CS project for mass public engagement. But one thing is certain, the appetite for citizens to be involved in scientific discovery is growing, especially in the Polar Regions and it shows no sign of waning. Studies have shown that at the centre of a successful CS programme is the stimulation and quality of participation. Shirk et al (2012) state that the design and implementation of every project require decisions to be made about (a) whose interests can and should be addressed, and (b) how the end goals are defined. These choices define the direction of the project, and the interests of whom the project is serving. Furthermore, the quality of public participation and engagement depends upon sufficient attention to public interests at the initial design stage, such as to identify questions and structure activities most likely to yield outcomes relevant to those interests. Most successes come about when both the public and the scientific community come together to determine the focus of a project i.e. equality in the co-production and co-design of the project.

The general framework underlying public participation in a CS project is shown in Figure 1. This figure comes from Shirk et al, (2012) and shows clearly the sequential transition from the input of interests from science and public, through to activities, outputs, outcomes and finally the measured impact of the project.

[2] For more information see: https://en.wikipedia.org/wiki/SETI@home

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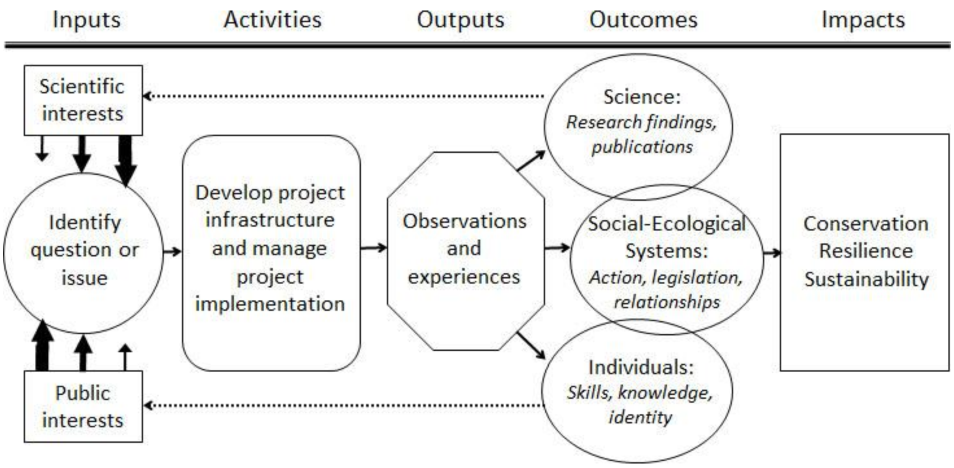

Figure 1. Framework for public participation in scientific research projects involved in studying an ecological system (from Shirk et al, 2012).

Shirk et al. (2012) explain that each of these five elements is interlinked to the next element, but they should be considered as separate activities that need equal consideration. These elements are explained in more detail below

I. **Input:** Are the interests of both the public and the scientific community as they co-produce the aims and objectives of a project. This includes defining questions for the project to answer, as well as the vision, goals, expectations, and so on.

II. **Activities:** Are where the bulk of the work that is necessary to design, establish, and manage all aspects of a project

III. **Outputs:** Are the initial products, data, or analysed results of the activities. Given the broad nature of CS activities outputs will vary depending on each project's objectives.

IV. **Outcomes**: Are measurable aspects of the project, such as skills, abilities, and knowledge that result from the specific outputs. Outcomes are generally short-term, and are typically measured over 1 to 3 years.

V. **Impact:** Are long-term and sustained changes that support improved understanding, well-being or have driven changes in policy. They generally occur many years after projects have been established

Figure 1 reveals how projects must balance the inputs from scientific interests and public interests. The exact balance is a matter for negotiation within each project, and as such the balance will be different depending on the needs of that project (as represented by input arrows of different sizes). Projects also exhibit different outcomes for (a) science, (b) individuals i.e. researchers or volunteers, and (c) for social-ecological systems. Shirk et al. (2012) note the feedback arrows, which show certain outcomes, may focus on different interests as initiatives as the CS project evolves.

The motivation of the coordinators and the participants, both scientist and citizen, is a key component of any CS project. Based on a series of studies, which were mostly in the fields of ecology, biology and nature conservation, See et al. (2016) summarised the different volunteer motivations as:

- the desire to learn more about the science behind the project;

- helping the environment; getting to know other people with similar interests and as a way to make new friends;
- feeling like an active participant and co-owner of the project; relevance to the community;
- ability to see the impact of their work, e.g. visualization of their data collection efforts or further use within a scientific or policy application; and
- gaining recognition for their input, e.g. through feedback and interaction with scientists and peers, and through gaining achievements, e.g. progression to expert status or from simple to more complex tasks requiring additional responsibility. Where possible, tasks should also be fun and participation should be made as easy as possible, minimizing technical, logistical, legal and intellectual barriers

Motivation is a constant challenge, but CS projects that can motivate their participants, both scientists and citizens, over the long-term are likely to be more successful. However, there is no magic bullet guaranteeing the success, but Shirk et al (2012) suggest that the success of project outcomes are influenced by the:

1) degree to which the public participates in the research process, as well as the quality of that participation, are closely related to the range and types of outcomes achieved;

(2) quality of public participation as negotiated during project design i.e. a common framework to inform project design choices across fields of practice

It is not an easy process developing, and running, CS projects that provide an innovative approach to pressing scientific issues. It takes time and effort, and working within a transparent and inclusive sphere of CS can be challenging. The project coordinators must proactively engage with a diverse range of participants from different age groups and cultures, and they must ensure management/decision relationships are transparent and easily understood. At the same time they must keep the motivation high, encourage both ownership and accountability amongst participants, and be flexible enough to adapt activities to evolving conditions (Wulfhorst, et al., 2008).

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Chapter 3: Options to enable CS to better interact and enhance the use of *in situ* observations by the Copernicus Services

As one of the biggest distributors of environmental products and services in Europe the Copernicus Services should play a proactive role in (a) making sure their products are usable by CS projects, (b) ensuring CS projects can enhance the accuracy and usability of their products. Citizen science will continue to develop and diversify and as it does Copernicus Services will have an opportunity to enhance its relevance and the uptake of its products by the citizens of Europe, which will increase their reputation and their role within society.

Big institutes playing a proactive role in CS is not an unusual concept, both NASA and ESA have partnered with CS projects and a quick web search revealed (as of July 2020):

- NASA: has over 20 presently active collaborations with CS projects that use NASA data, see https://science.nasa.gov/citizenscience.
- ESA: whilst not as prolific and NASA, it has initiated and funded several programmes aimed at CS activities. These include:
  - Collaborated with the EducEO project which aimed to better understand how the emergence of millions of passionate Citizen Scientists could be capitalized to make the most of Earth Observation products. Although it is not clear if this project is still running or what the outcomes were. See: http://educeo.vtt.fi/
  - Citizen Science Earth Observation Lab (CSEOL) is an initiative that was funded by ESA for CS app development aimed at satellite validation activities. CSEOL is currently in its implementation phase: https://cseol.eu/ with the first Pilot Projects due to report at the end of 2020.
  - More recently ESA joined the Earth Challenge 2020 consortium of strategic partners to work together in addressing major issues. The involvement of citizens is fostered, among others, through the Earth Challenge 2020 App that features several thematic widgets.

Whilst growing the visibility and usage of Copernicus products by European (and global) citizens through CS projects is welcome, there can be operational incentives for more focused collaboration between CS projects and Copernicus. See et al. (2016) rightly points out that the present and future *Sentinel* missions will require better access to calibration and validation (CalVal) on different temporal and spatial scales. The combination of limited budgets and growth in data acquisition, means new sources of Cal/Val need to be considered, particularly those from CS. We believe the same approach could be made for many of the Copernicus products and services, for example, Copernicus-relevant CS initiatives could be focused specifically on the calibration and validation of Copernicus products. The challenge is how to best integrate the operational needs of Copernicus with the willingness of citizens to participate in scientific endeavours.

For scientists, citizens and policymakers there is an increased need to find answers to some of the most pressing societal challenges such as environmental pollution, declining biodiversity or climate change, and others particularly relevant for the Arctic. Citizen science can, and will, play a more prominent role in decision making, and as it does the Copernicus Services must embrace the opportunity to develop fruitful partnerships with the public through building CS capacity within their Services.

Hecker et al., 2018, suggests that the most important lesson from capacity-building programmes is the need for an in-depth understanding of their stakeholders and actors. As we have shown CS is a broad field, and actors share different goals and approaches. Capacity building involves five main steps (Hecker et al., 2018):

(1) identifying and engaging different actors,

(2) assessing capacities and needs for citizen science in the setting under focus,

(3) developing vision, missions and action plans,

(4) developing resources such as websites and guidance, as well as

(5) implementation and evaluation of citizen science programmes.

This is not an easy process but strategic capacity-building programmes have been initiated at the European level through the development of a Green Paper for Citizen Science in Europe[3], and at the national level, for example the Green Paper Citizen Science Strategy 2020 for Germany[4]. Both provide a good source of information that could, amongst other things, act as a guide to CS capacity building within the Copernicus Services.

Part 1 Recommendations and suggestions

For the Copernicus Services to capitalize on the broad potential of CS we suggest:

- Copernicus Services should make a greater effort to highlight and grow the number of CS projects using their products or validating their products.
- One Copernicus Service, or most likely the presently under-utilised Copernicus *In Situ Component*, is encouraged to take ownership/stewardship of CS needs and interaction for all Copernicus Services.

The Copernicus lead for CS is encouraged to:

- recruit or support a small number of CS experts to develop an achievable strategy that would allow for a more integrated approach to CS by the Copernicus Services.
- perform an audit of the interaction between CS and the different Copernicus Services.
- develop mechanisms to encourage, support and facilitate more CS projects to be involved in the Cal/Val of the present and future Copernicus products and services.
- pursue channels of communication with the European Citizen Science Association, the H2020 funded EU Citizen. Science project, and other leading CS organisations within Europe. The aim is to support and advance European CS through better communication,

[3] https://ciencia-ciudadana.es//wp-content/uploads/2018/09/GreenPaperOnCitizenScience2013.pdf
[4] https://www.buergerschaffenwissen.de/sites/default/files/assets/dokumente/gewiss_cs_strategy_englisch.pdf

coordination, and knowledge sharing with the focus being on strengthening the goals to and maintain the capabilities of the Copernicus Services.

The evidence suggests that CS can make a welcome contribution to enhancing the relevance of the Copernicus Services to European citizens, as well as helping to evaluate and improve the accuracy of Copernicus products themselves. Addressing the above-mentioned suggestions should provide a pathway for the data collected by citizens to become a serious and important part of Copernicus Services in the future, especially the Copernicus *In Situ Component*.

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Part 2. *In situ* observations

The world is presently on a trajectory to warm by about 2°C in less than 40 years, with the Arctic region set to warm substantially faster. These changes have significant social, economic and environmental consequences, which in turn have an impact on the ecosystem and its dynamics on local to global scales. The rapid pace and highly dynamic interactions of these changes push the Arctic climate into a regime unlike anything humans have previously lived through. In this situation, unrestricted and timely access to scientific observations are crucial to allow evidence-based decisions that lead to a safe, sustainable and prosperous Arctic. These same observations are, indirectly via Arctic-mid-latitude linkages, connected to a safe, sustainable and prosperous Europe.

To best overcome these challenges, information on the status and evolution of the Arctic environment is crucial. Unrestricted and timely access to *in situ* scientific observations and model forecasts underpins evidence-based decision making. Within this section of the report we assess how the observational research community, both **marine and terrestrial**, can better contribute to *in situ* monitoring to improve Polar Regions products of the Copernicus Services. To do this we have summarised information and recommendations from previous reports, as well as performing an in-depth consultation process with research infrastructure stakeholders. Finally, we provide a series of suggestions on how the marine and terrestrial polar research community can better interact with the Copernicus Services, for the mutual benefit of both, but especially in the improvement of products and services.

To clarify, Copernicus services for the **marine sector** include:

- the Marine Environmental Service (CMEMS) and
- the Maritime Surveillance Service (CMS).

For the **terrestrial sector** include:

- Copernicus Land Monitoring Service (CLMS)

And covering **both marine and terrestrial:**

- Copernicus Atmosphere Monitoring Service (CAMS)
- Copernicus Climate Change Service (C3S)
- Copernicus Security Service (CSS)
- Copernicus Emergency Management Service (Copernicus EMS)

There is no dedicated Copernicus service for either the Arctic or Antarctic.

Chapter 4: Current status of Arctic *in situ* measurements

Within the timeline of KEPLER (and this Deliverable 3.1) the European Environment Agency's (EEA) contracted a report regarding the implementation of cross-cutting activities for coordination of the *in situ* component of the Copernicus Programme Services. In 2019, Buch et al[5] delivered this report entitled, 'Arctic *In situ* Data Availability', to the EEA. The objective of this report was to provide an analysis of:

- the requirements for meteorological and ocean (including sea ice and cryosphere) *in situ* data in the Arctic region by Copernicus Services and Space Component. Land observations were not included in the project mandate;
- the existence and availability of the required data including identification of conditions for access to restricted data (payment, limitation in use, etc.); and
- any gaps identified in the observation system.

This report did a good job in providing (i) an overview of requirements for the Arctic *in situ* data, (ii) a summary of existing *in situ data* used by, or relevant to, Copernicus, and finally (iii) performing a gap analysis regarding *in situ* data from the Arctic.

Boiling down the information within this report we find that it calls upon the Copernicus Services to develop strategies to effectively respond to:

(a) how Copernicus uses *in situ* data,

(b) what are the requirements of these data,

(c) how Copernicus can improve access to, and gathering of, Arctic *in situ* data and

(d) how Copernicus *in situ* component can be more relevant to its stakeholders, including the research community.

In summary, to overcome these shortcomings they suggested Copernicus needs to initiate eight activities to:

1. **establish** clear requirements on Copernicus' need for the Arctic *in situ* data with special attention on:
    i. resolution in space and time,
    ii. data quality improvement, and
    iii. metadata improvements;
2. **establish** formal links to intergovernmental bodies such as SAON[6], WMO[7], IOC[8] and GEO[9] to:
    i. promote Copernicus requirements, and
    ii. to facilitate an international recognition and focus on the gaps in the collection of environmental *in situ* data in the Arctic particularly in the central Arctic Ocean;

[5] available from: https://insitu.copernicus.eu/library/reports/CopernicusArcticDataReportFinalVersion2.1.pdf
[6] Sustaining Arctic Observing Networks: https://www.arcticobserving.org/
[7] World Meteorological Organization: https://public.wmo.int/en
[8] Intergovernmental Oceanographic Commission of UNESCO: http://ioc-unesco.org/
[9] Group on Earth Observations: https://www.earthobservations.org/index.php

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3. **enhance** international cooperation between EU and non-EU countries with Arctic interests, e.g. Canada, China, Korea, Japan, Russian and USA in a global context of data sharing;
4. **liaise** with Horizon Europe to promote that:
   i. Arctic relevant observing technology and data communication development is included in future research calls – focus could be on multi-purpose and autonomous observing platforms, and
   ii. research projects are requested to secure a free exchange of data along the FAIR principle using existing European data management infrastructures;
5. **pursue** innovative cost-effective technological solutions for Arctic observations securing continuous Near-Real-Time (NRT) data flow from this harsh environment also during wintertime;
6. **initiate** a data rescue activity composed of but not limited to the following components:
   i. continuous support of projects like the C3S 311a inventory effort, enhanced data collection, homogenization and mining,
   ii. establish centralised data portals similar to CMEMS In Situ Thematic Centre (INSTAC) for all thematic domains,
   iii. start a task force focusing on unlocking existing data presently not available to Copernicus. The effort could include support to organisations without a proper data management structure, support to the implementation of proper data quality control procedures;
7. **work** with national authorities to:
   i. secure sustainable funding for a fit-for-purpose Integrated Arctic Observing System,
   ii. support initiatives toward NRT delivery of data, and
   iii. increase the involvement of indigenous people in data collection;
8. **initiate** the development of a European counterpart of Operation IceBridge.

Chapter 5: KEPLER Consultation process

Our consultation process was aimed at assessing how the observational research community, both **marine and terrestrial**, can better contribute to *in situ* monitoring to the aims of Copernicus.

5.1. Terrestrial research consultation process.

INTERACT (ULUND) consulted their terrestrial Infrastructure Network to better assess how:

(i) the terrestrial observational research community access Copernicus products,
(ii) they cooperate with the Copernicus services, and to recommend solutions to identified gaps.

A KEPLER Milestone report entitled 'INTERACTers' view on research and capacity gaps in Satellite Earth Observations' was produced describing the output of this consultation. A summary is performed below. A breakdown of the answers to the questionnaire can be found in Appendix B at the end of the document.

What is INTERACT - *https://eu-interact.org*

INTERACT is a pan-Arctic network of currently 88 terrestrial field bases in northern Europe, Russia, US, Canada, Greenland, Iceland, the Faroe Islands and Scotland, as well as stations in northern alpine areas. This long-term project, which is funded by the EU, has the main objective to build capacity for identifying, understanding, predicting and responding to diverse environmental changes throughout the wide environmental and land-use envelopes of the Arctic. This is necessary because the Arctic is so vast and so sparsely populated that environmental observing capacity is limited compared to most other latitudes.

INTERACT station managers and researchers have established partnerships that are developing more efficient networks of sensors to measure changing environmental conditions, and these partnerships are also making data storage and accessibility more efficient through a single portal. New communities of researchers are being offered access to terrestrial infrastructures while local stakeholders, as well as major international organisations, are involved in interactions with the infrastructures.

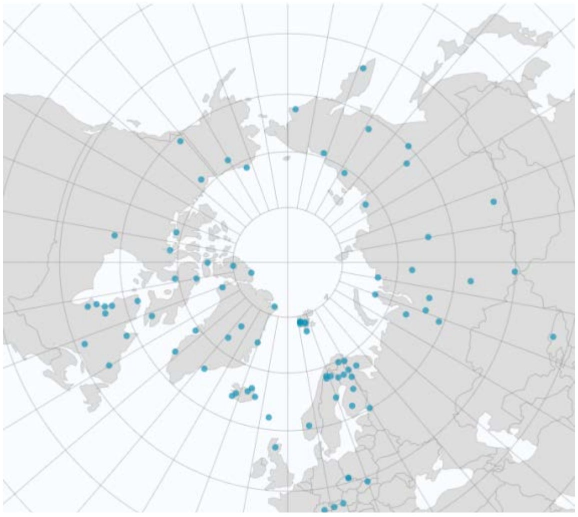

Figure 2. *INTERACT is a network of 88 research stations located in all Arctic countries and adjacent high alpine areas.*

5.1.1 The Survey

To compile the INTERACTers' view on research and capacity gaps in Earth Observations, and to understand if there is adequate access to *in situ* observing systems, a workshop was organized at Vindeln, Sweden, on the 12 September 2019. To reduce the carbon footprint associated with the survey it was performed back to back with INTERACT's General Assembly. During the workshop, Mentimeter (www.mentimeter.com) was used. This is presentation software that allows you to ask the participants questions in your presentation and afterward display the result. This made it possible for the participants to instantly see and discuss the result. 33 INTERACTers participated in the workshop, whereof 15 were women and 18 were men.

A complimentary survey questionnaire was sent out to all station managers after the workshop to allow INTERACTers' that was not participating at the meeting to contribute to the survey. Eight additional answers were received from the complementary online survey. The survey consisted of 15 questions and the results are described in the following section, but the results of individual questions can be found in the Appendix at the end of this document.

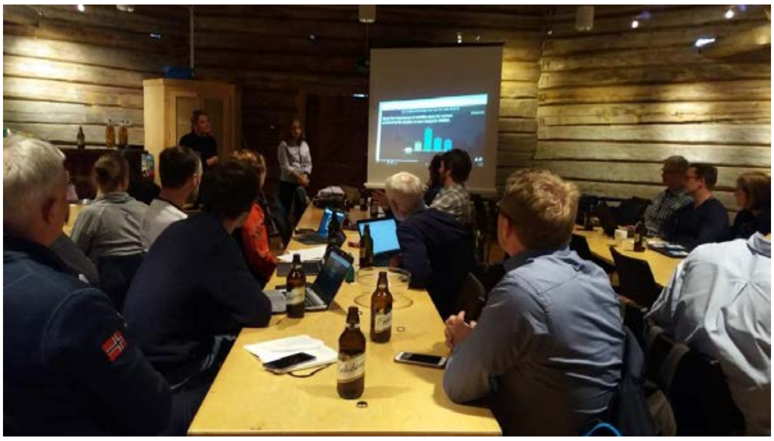

Figure 3. *Workshop in Vindeln, Sweden to identify, from the terrestrial observational research community, how they access Copernicus products, how they can contribute to the aims of Copernicus, and to recommend solutions to identified gaps.*

Our finding suggested that little more than half of the INTERACT research stations that contributed to this survey are using satellite data. It might be that many of the researchers that are using remote sensing data are not using it at the research stations, but are working with EO at their home institutes instead. This survey was sent to the station managers, and likely the response would have been different if it was sent to the researchers who use the stations instead. However, as INTERACT research stations are annually hosting more than five thousand researchers that would not have been feasible. In addition, many of the research stations have an extended monitoring programme which might be why satellite data might not be that important for the station.

5.1.2 Key findings

- *Lack of interaction or cooperation between the INTERACT's network of Arctic research stations and the Copernicus Services.*
- *INTERACT, through its vast network of terrestrial research stations spanning the entire Arctic, has great potential to become a ground validation and calibration network for Copernicus products and services. This potential is yet to be realised.*
- *INTERACT wants to better contribute to the aims of Copernicus in the future, and one way to do it might be through Virtual Access (found on INTERACT's website eu-interact.org) that could contribute to ground validation in the future. Better interaction between the Copernicus Services and INTERACT is needed.*

5.2. Marine research consultation process.

A consultation with the marine sector was performed by WP 1.1[10] of KEPLER, and this was supplemented with input from a maritime dialogue session at Arctic Circle, Iceland, as well as previous reviews on this topic (generally led by the European Ice Services, EIS). The EIS has amassed a great deal of experience and knowledge liaising between stakeholders, end-users, research groups and academic institutes. More recently, the EIS was involved in the Arctic Sea Ice Prediction Stakeholders Workshop" (ASIPSW), and the "Saliency of climate services for marine mobility Sectors in European Arctic Seas" (SALIENSEAS) project, part of the European Research Area Network (ERA-NET). Some of the more pertinent marine-based recommendations from these workshops are listed below.

Key findings from ASIPSW/SALIENSEAS :

- *Better communication with users to make them aware of the range of met-ocean services available.*
- *Need for more co-production of decision-making systems to educate users on potential new products and services, and tailor solutions to industry needs.*
- *Create an iterative process for product development that allows for synergies and a better understanding of respective skills, limitations, and promotion of better tools.*
- *Create better visualisation tools, taking into account low bandwidth limitations.*
- *Link to complementary programmes and initiatives focusing on the links between industry needs and forecasts.*

[10] D1.1. Stakeholder Needs: Maritime Sector Needs. Lead Author: Penelope Wagner, Norwegian Meteorological Institute - Norwegian Ice Service

Chapter 6: European Terrestrial and Marine in situ observational research communities

Europe has a flourishing and active Polar research community, at a national, European and international level. On the European stage, there are three main organisations/programmes that are involved in a broad range of European funded polar research. These are the (1) European Polar Board, (2) EU-PolarNet and (3) the EU Polar Cluster. There are many other organisations and networks with a high level of European participation, such as the Svalbard Integrated Arctic Earth Observing System (SIOS), but these are more concerned with a particular region of the Arctic (such as Svalbard), or focus on a single discipline (such as permafrost).

6.1. European Polar Board

The European Polar Board[11] (EPB) was established by the European Science Foundation in 1995, and since 2015 it has been an independent entity with its Secretariat hosted by the Dutch Research Council (NWO) in The Hague. The EPB focuses on major strategic priorities in the Arctic and Antarctic research, promotes multilateral collaborative activities between Members, and provides a single contact point for the European Polar research community as a whole for international partners.

EPB's vision:

- a strong and cohesive European Polar research community, wherein decisions affecting or affected by the Polar Regions are informed by independent, accurate, and timely advice from the EPB.

EPB has a mission:

- to improve European coordination in Arctic and Antarctic research through improved information sharing, optimised infrastructure use and joint initiatives between Members.

EPB Members include research institutes, logistics operators, funding agencies, scientific academies and government ministries from across Europe.

6.2. EU-PolarNet

EU-PolarNet[12] is the world's largest consortium of expertise and infrastructure for polar research. Seventeen countries are represented by 22 of Europe's internationally-respected multi-disciplinary research institutions. EU-PolarNet began in 2015 and will run to 2020. Together the EU-PolarNet team has developed and delivered a strategic framework and mechanisms to prioritise polar science, optimise the use of polar infrastructure, and broker new partnerships that have led to the co-design of polar research projects; all of which have delivered tangible benefits to society. EU-PolarNet adopts a higher-degree of coordination of polar research and operations, and thus engages in closer cooperation with all relevant actors on an international level. EU-PolarNet works closely with the EPB, and thus outcomes from EU-PolarNet add long-term value to EPB activity in providing strategic science policy advice to the European Commission and other international bodies.

Note: The EU-PolarNet has just won funding to continue its work for a further five years, under the name of EU-PolarNet2.

[11] see http://www.europeanpolarboard.org/
[12] see https://www.eu-polarnet.eu/

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6.3. EU Polar Cluster

The EU Polar Cluster[13] (previously the EU Arctic Cluster) is a collaboration of large multidisciplinary Arctic and Antarctic projects funded by the European Commission. The EU Polar Cluster (EUPC) currently comprises of 15 Horizon 2020 and a Framework Programme 7 (as of April 2020). These include: APPLICATE, ARCSAR, ARICE, Beyond EPICA, BLUE-ACTION, EU-PolarNet, FORCeS, ICE-ARC, iCUPE, INTAROS, INTERACT, KEPLER, SO-CHIC, TiPPACS, and NUNATARYUK.

Because the above-mentioned projects cover a wide variety of sectors and disciplines the EUPC brings together a broad spectrum of research and coordination activities – ranging from the most up-to-date findings on permafrost and sea ice, through to enhancing observation to improving predictions, and from networking research stations through to coordinating access to icebreakers.

The objective of the EU-PC is:

- to bring insights from the various areas of expertise together to provide one entry point to EU funded Polar research. Jointly we aim to provide policy-relevant information to support the EU in implementing its integrated policy for the Arctic.

6.3.1 EU-PolarNet workshop recommendations

An EU-PolarNet workshop, held at Arctic Frontiers in 2018[14], had the theme of "Connecting the Arctic". Whilst the output of this workshop was not directed towards the Copernicus Services or the more efficient use of *in situ* data, we find some of their recommendations poignant to the central theme of this deliverable. These recommendations are listed below:

- a need for improved and ongoing communication between space agencies and the polar research community;
- the national space agencies need to coordinate better with the polar research community, and be better integrated into satellite planning efforts;
- relevant polar operators and scientists should be included in advisory and expert groups for space activities to represent the research community needs;
- national polar operators should develop engagement plans with representatives to the ESA and EC space programs to represent their requirements where possible.

Interestingly, these recommendations are very similar to the findings of the INTERACT consultation process mentioned above (Section 2.1 Terrestrial research consultation process). For example, the EU-PolarNet workshop suggested better communication is desperately needed between the research community (including polar infrastructure operators) and space agencies. Whilst, the output of the INTERACT consultation recommended better communication between the Research Stations and the Copernicus Services. Whilst the themes are slightly different the sentiment is the same; better communication and dialogue with the research community is needed.

Liaison between space agencies and the polar research community is currently handled by the Polar Space Task Group[15] (PSTG), established in 2011 and managed by the WMO Executive Council Panel of

[13] see https://www.polarcluster.eu/
[14] see report: Stakeholder Sea Ice Forecast Workshop and SALIENSEAS Stakeholder Advisory Group
[15] PSTG chair is Mark Drinkwater (ESA)

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Experts on Polar and High Mountain Observations (EC-PHORS). The group is constituted of representatives of nearly all the space agencies, and has the mandate to provide coordination across space agencies to facilitate acquisition and distribution of fundamental satellite datasets, and to contribute to or support the development of specific derived products in support of cryospheric scientific research and applications. The relationship to other bodies is shown in the schematic below (Fig. 4). It should be noted that at present the WMO is undergoing reorganisation, and the future status of the group is uncertain.

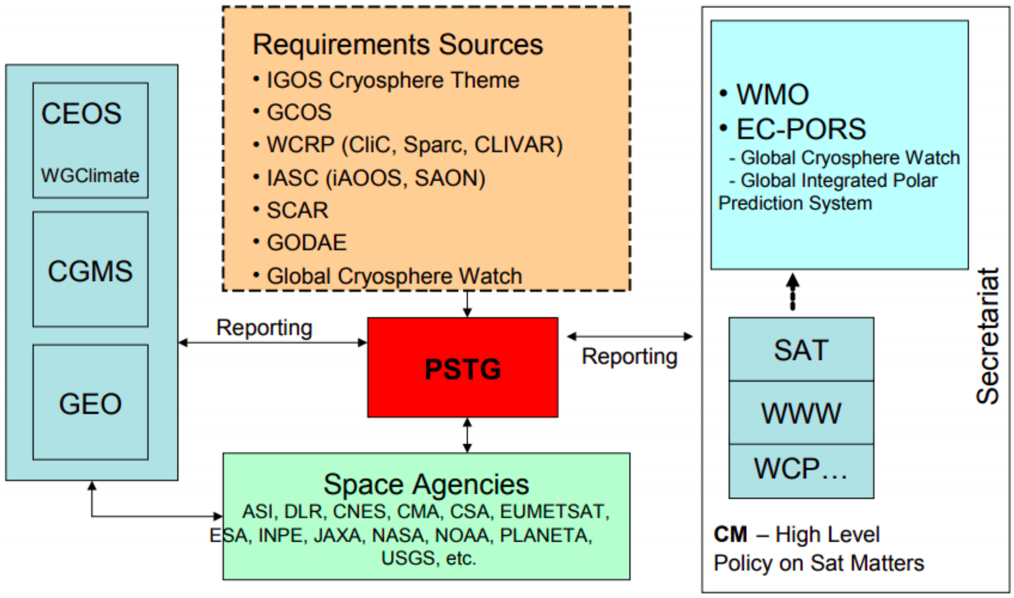

Figure 4. *The organisational 'ecosystem' in which Polar Space Task Group operates*

6.4. Meeting between KEPLER, the EEA, and INTAROS

During the KEPLER project a series of meetings were held with the European Environment Agency[16] (EEA) and the EU Polar Cluster project INTAROS[17]. These meetings aimed to:

a) better understand each other's activities and to explore synergies and mutual information,
b) discuss possible ways to cooperate and support each other to avoid duplication of work,
c) provide initiatives towards an open and free exchange of data,
d) discuss requirements for a sustained arctic observation network.

During our discussions it became clear that KEPLER could offer recommendations for use in a presentation at the upcoming meetings of the EU Polar Expert Group (PEG-3). Unfortunately, the meeting was postponed due to the COVID-19 situation and is now happening in late summer 2020. Another output from this meeting was the planned development of a white paper that provide constructive recommendations for the Copernicus *In Situ* Component for the Copernicus 2.0 contract period (2021-2028). This white paper would be based upon the findings we have achieved within KEPLER and INTAROS regarding the Arctic *in situ* observing systems.

6.5. Key findings

Despite Europe having a well-connected and collaborative polar research community, through the EPB, EUPC and EU-PolarNet, we could not find many links between the Copernicus Services and these three key European organisations/programmes. There are links between individual Copernicus Services with individual EU Polar Cluster[18] projects, such as those within KEPLER. However, this type of participation in an EU Polar Cluster programme seems to be more due to informal network connection between individuals, rather than from a push from the Copernicus Services themselves. The European Space Agency (ESA) is more advanced in its dealings with the European Polar Community, for example it has signed a Memorandum of Understanding (MoU) with the European Polar Board.

Note: In 2020 the EU released a €15 million call for proposals addressing the Topic *LC-CLA-20-2020: Supporting the implementation of GEOSS in the Arctic in collaboration with Copernicus.* It is hoped this will act as a catalyst for the development of a close relationship between the Copernicus Services and the EPB, EU-Polarnet2 and the EUPC.

Chapter 7: Calibration and Validation: a possible route to closer cooperation

Information from Copernicus (and other space agencies like ESA) is used to support operational monitoring activities such as production of ice charts, maritime navigation, weather forecasting,

[16] The European Environment Agency provides sound, independent information on the environment for those involved in developing, adopting, implementing and evaluating environmental policy, and also the general public. In close collaboration with the European Environmental Information and Observation Network (Eionet) and its 32 member countries, the EEA gathers data and produces assessments on a wide range of topics related to the environment. See https://www.eea.europa.eu/

[17] INTAROS has the overall objective of building an efficient integrated Arctic Observation System (iAOS) by extending, improving and unifying existing systems in the different regions of the Arctic. See http://www.intaros.eu/

[18] For example, the KEPLER programme has direct involvement of many Copernicus centres and associated institutes. Take CMEMS for example, Mercator Ocean International (coordinates CMEMS), as well as MET Norway, DMI, FMI SMHI, BAS, NERSC, CSIC, and AWI are all involved.

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environmental impact analyses, emergency response, and so on. These products are also regularly utilised by researchers whose needs vary considerably depending on the science they are delivering. For example, research into climate change needs consistent data-streams over long periods, whilst research into a short-lived phenomenon, such as a storm event, needs a number of products, but over a shorter period. The commonality linking the needs of both the operational and the research communities is the need for accurate products, with known uncertainties. Thus, an ongoing campaign of validation and calibration (Cal/Val) throughout a product's lifetime is mandatory.

ESA, for example, has an improving record of Cal/Val and Table 2 lays out their Cal/Val needs for their different missions. We can see that the parameter sea level rise (under an ocean thematic area), sits under five missions (a) S-3, (b) CryoSat, (c) S-3 NG, (d) CRISTAL, and (e) SKIM and the calibration of the sensors within these missions are performed by tide gauges, moving vessel profiler (MVP), gliders, CTD, Argo buoys, drones. This table covers both Marine (named Ocean and Sea–ice) and Terrestrial (named Land-ice) thematic areas, as well as present and future missions, and also the potential *in situ* sensors that can be used to validate/calibrate a Mission's product. It would be advantageous for a similar table to be produced for each of the Copernicus polar products.

Example of ESA needs for in-situ measurements in Arctic for Cal/Val

Thematic area	Parameters	Missions	Potential Insitu sensors
Ocean validation			
	Sea level (sea surface height)	S-3, CryoSat, S-3NG, CRISTAL, SKIM	Tide gauge, Moving vessel profiler (MVP), Gliders, CTD, Argo buoys, Drones
	Ocean wave	S-1, S-3, CryoSat, S-3NG, CRISTAL, SKIM	Tide gauge, buoys
	Sea surface gradients/current	S-1, S-3, CryoSat, S-3NG, CRISTAL, SKIM, Steroid	Moving vessel profiler (MVP), Gliders, CTD, ADCP, drifting buoys, HF radar, drones
	Sea surface temperature	S-3, S-3NG, CIMR	SST radiometers, MVP, gliders, CTD
	Sea surface salinity	SMOS, CIMR	MVP, gliders, CTD
	Ocean colour (CHL, LIGHT, CDOM,…)	S-3	Chlorophyll-fluorescence, light and other optical sensors on BioArgo, gliders, buoys
Sea-Ice validation			
	Sea ice thickness	S-3, CryoSat, S-3NG, CRISTAL, SMOS, CIMR	Boat and airborne campaigns, submarine data, drifting buoys
	Sea ice freeboard	S-3, CryoSat, S-3NG, CRISTAL, SMOS, CIMR	Boat and airborne campaigns, submarine data, drifting buoys
	Snow depth (+temperature and salinity)	S-3, CryoSat, S-3NG, CRISTAL, SMOS, CIMR	Boat and airborne campaigns,
	Sea ice drift	S-3, S-3NG, SKIM, S-1, S-2, steroid (?)	Boat and airborne campaigns,
	Iceberg drift, size and thickness	CryoSat, S-1, S-2, S-3, CRISTAL	Boat and airborne campaigns
Land-Ice validation			
	Ice sheet spectral albedo, broad band albedo	S-3, S3-NG	Campaigns, surface-mounted radiometers
	Ice sheet snow grain size distribution	S-3, S3-NG, S-2	Campaigns
	Ice sheet surface temperature	S-3, S3-NG, LSTM (Copernicus LST), CIMR	Campaigns, surface-mounted temperature sensors
	Ice sheet surface elevation	S-3, S3-NG, Cryosat, CRISTAL, SKIM	Campaigns
	Ice sheet surface velocity	S-1, S-2	Campaigns, GPS trackers
	Ice sheet/shelf calving front location	S-1, S-1NG, ROSE-L, Cryosat, Cristal	Campaigns
	Terrestrial snow depth/density or snow water equivalent	MWI, CHIME, ROSE-L	Campaigns
	Soil state freeze and thaw	SMOS	Campaigns
	Permafrost active layer seasonal subsidence	S-1, S-1NG, ROSE-L	Campaigns

Table 2. This table shows an example of ESA's needs for in-situ measurements in the Arctic for the calibration and validation of their missions for both marine and the terrestrial Arctic focused missions. Courtesy: M. Drinkwater. Note we added the parameter ocean colour to Ocean Validation. It is important to note that in many instances Citizen Science projects can play a role in using sensors to monitor these parameters.

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7.1. Thematic Data Assembly Centers (TACs)

Two of the major themes running through our dialogue with the marine and terrestrial observational research community is (a) the need for better dialogue with the Copernicus Services, and (b) the beneficial role observational research community can play in validation and calibration of Copernicus polar-focused products, especially through the unrivalled access the European research community has to research infrastructure (research stations, aircraft and icebreakers). Through these two mechanisms, better communication and Cal/Val, the Copernicus and the research/operational communities can begin a more constructive working relationship to the mutual benefit of both.

A possible starting point for better collaboration between the *in situ* research community, the operational community and the Copernicus Services who produce Arctic products could be through the Thematic Assembly Centers (TAC)[19]. The TAC's process data acquired from satellite and *in situ* observations into near-real-time products, as well as historic products. For example, with CMEMS there are presently eight TAC, and each provides products that are useful for the Arctic (see KEPLER Deliverables: D2.1[20], D2.2[21] , D3.3[22] and D6.6[23] regarding useful Arctic products). These are:

1. Sea Ice TAC
2. Surface Wind TAC
3. Sea Level TAC (Sea Level Satellite Data)
4. In Situ TAC (*In situ* temperature, salinity, currents and other variables)
5. Ocean Colour TAC (Ocean Colour Satellite Data)
6. Sea Surface Temperature TAC
7. Wave TAC
8. Multi Observations TAC

Collaborating with the TACs, the European polar research community could help with calibration and quality control of Copernicus polar products. The TACs already provide a QUID (QUality Information Document) that provides details on the audit of science quality control for a CMEMS product. This is based upon a common validation method for the different products following conventions laid out in the CMEMS Cal/Val guidelines. However, the Polar Regions have data that is at best sparse, and therefore it is not possible to follow established and validation conventions (see as an example the QUID for OSI TAC Sea Ice products).

[19] https://marine.copernicus.eu/about-us/about-producers/
[20] Final report on ways to improve the description of the changing Polar Regions in the Copernicus Land Monitoring Service.
[21] Final report on ways to improve the description of the changing Polar Regions in the Copernicus Marine Environment Monitoring Service.
[22] Research gaps of space-based Arctic monitoring.
[23] Best practice guide for EO information use by research vessels and stations.

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Table 3 displays the results of an evaluation of the QUIDs for a number of Copernicus products for the Polar Regions. The results clearly show that **the validation and quality control of many, if not all, Copernicus products within the Polar Regions is at best poor**. Major shortfalls include

(i) Significant lack of *in situ* observations, possibly combined with the lack of knowledge of where to access some datasets[24], meant that the protocols laid out in the CMEMS Cal/Val guidelines cannot be performed.

(ii) Evaluations that are performed in the Polar Regions do not run over an annual cycle, or in different Polar Regions, and therefore resultant products may not be representative,

(iii) A general acceptance that the quality of a polar product may be inferior to mid-latitude regions, but with no mechanism to investigate possible solutions, and

(iv) Instances where no validation is performed in the Polar Regions. Therefore, the accuracy of product in these regions cannot be assessed.

Thematic Data Assembly Center (TAC)	***Direct quotes from QUID documents regarding Arctic or Antarctic in situ data***
1. Sea Ice TAC[25]	***'Significant lack of useful in situ observations with which to compare the satellite data****. This is true of all the variables provided in the sea ice products: concentration, ice edge, ice type, ice drift, iceberg concentration, ice surface temperature. The in situ observations that are available are spotty and intermittent in time. It is therefore very* ***difficult to calculate sound statistics for the global datasets and nearly impossible for the regional datasets****.'*
2.Surface Wind TAC[26]	*'Inspection of individual cases and by buoy collocations for a period of one year (2019), and by inserting artificial inputs to the gridding procedure and comparing input and output fields to an exactly known input function.'* ***No mention of Arctic, Antarctic, or polar in the document, thus we suspect no validation in these regions was performed.***
3.Sea Level TAC[27]	*'The quality of the REP/DT DUACS products has been assessed by comparison with independent measurements (in situ and satellite) and in coordination with other projects (Copernicus C3S and CNES SALP). It mentions that '****the altimeter standards used in the Arctic region NRT processing have improved****.' 'The use of the MSS CNES_CLS15 over the Arctic region leads to an improved consistency between global and Arctic products.'* The **document does not mention if any *in situ* Arctic data was utilized in the analysi**s.

[24] This is a recognised problem with in situ data, some datasets are not easily accessible.
[25] https://resources.marine.copernicus.eu/documents/QUID/CMEMS-OSI-QUID-011-001to007-009to012.pdf
[26] https://resources.marine.copernicus.eu/documents/QUID/CMEMS-WIND-QUID-012-002-003-005.pdf
[27] https://resources.marine.copernicus.eu/documents/QUID/CMEMS-SL-QUID-008-032-051.pdf

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Thematic Data Assembly Center (TAC)	*Direct quotes from QUID documents regarding Arctic or Antarctic in situ data*
4.INS TAC[28]	*'In some regions the number of available platforms is on a critical low level to provide an adequate representative overall view of the state of the ocean. Within the Arctic most of the data is obtained by regular vessel cruises or dedicated scientific expeditions. The availability of data from these scientific expeditions is often delayed so they are not available for the RT data stream which results that the* ***data is not available for data assimilation of the operational models****.'* *'Within the Black Sea and in the* ***Arctic region critical low numbers of available observations impacting the provision of a good and representative real time data product is detected*** *within the temporal frame of the project*[29]*.'*
5. Ocean Colour TAC[30] *(For the Atlantic and Arctic Observation Products)*	*'The input dataset for the production of ARC and ATL REP was made available to CMEMS by the ESA Ocean Colour Climate. Statistical tests for OC5CCI versus the ARC in situ datasets with the higher number of match-ups. The values are* ***not as good as for the ATL area****, but this is not a surprise given the characteristics of the area, for example, low sun angles. The* ***correlation for the combined dataset is lower (r2 0.655) and the RMS error is substantially higher****.'*
6. SST TAC[31] *For Arctic Sea and Ice surface temperature product*	*'The quality of the L4SST and IST has been assessed for a 3 months period from August 2012 to December 2012 for the IST and for October to December 2019 for the SST part. The validation against independent in situ observations has been performed using drifting buoy observations from the CMEMS In situ TAC. In addition, Ice mass balance (IMB) buoys have been used to validate the ice surface temperature observations.* ***Note that the ice surface temperatures cover a limited region of the domain and that the three months might not be representative for the full year****. '*
7.Wave TAC[32]	*'The quality of the global wave model MFWAM run for 2016 and 2017 has been assessed by comparison with wave observations provided by satellite altimeters (HY-2A and S3A) and buoys. The validation has been implemented for the analysis of significant wave heights and peak wave period.'* *'The overall results demonstrate the good quality of the results, near the coast compared to buoys, and in the open ocean compare to satellite altimetry. The latter comparisons show that the* ***main biases are located in regions of high winds (the Antarctic Circumpolar Current).'*** *No mention of whether in situ Arctic or Antarctic wave measurements were used.*

[28] https://resources.marine.copernicus.eu/documents/QUID/CMEMS-INS-QUID-013-030-036.pdf
[29] We note the use of the word 'project', as this indicates a short-term, project-based thought-process, rather than that of a long-term service.
[30] https://resources.marine.copernicus.eu/documents/QUID/CMEMS-OC-QUID-009-066-067-068-069-088-091.pdf
[31] https://resources.marine.copernicus.eu/documents/QUID/CMEMS-SI-QUID-011-008.pdf
[32] https://resources.marine.copernicus.eu/documents/QUID/CMEMS-GLO-QUID-001-027.pdf

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Thematic Data Assembly Center (TAC)	***Direct quotes from QUID documents regarding Arctic or Antarctic in situ data***
8.Multi Observations TAC[33]	*'Thanks to the increase in the number of historical profiles available it is possible to obtain covariances that are more robust and having finer scale structures for almost the global ocean and the four seasons.* ***The Arctic Ocean remains strongly under-observed****.'*

Table 3. Table showing the 8 Thematic Assembly Centers (TAC) and some of their products that have applications to the Polar Regions. Notice that all have shortcomings, some very significant.

7.2 Key findings

- Lack of temporal and spatial *in situ* data in the Polar Regions is causing real problems in assessing the quality of Copernicus products for the polar regions. This means the quality assurance, calibration and validation are severely compromised.
- Some products for the Polar Regions may be inferior due to calibration and validation being performed at lower latitudes, or over limited spatial or temporal periods.
- Once the QUIDs have been produced we could find little evidence of incentives for developers to improve products, or to provide solutions to known inadequacies.

Part 2 Recommendations and suggestions

We found that there was a lack of dialogue between the broader European polar research and monitoring community and the Copernicus Services (and associated TACs). This in turn impacts the quality of Copernicus polar products and services. Recommendations and suggestions include:

- An independent scientific audit on the QUIDS with respect to the Copernicus Services polar products should be performed.
- Prioritising Cal/Val *in situ* measurements in the Polar Regions. This is desperately needed to reduce the identified uncertainties associated with Copernicus Services polar products.
- Developing a framework whereby Copernicus Services can better utilise European polar research assets (i.e. stations, ships, aircraft and people) to provide needed Cal/Val opportunities for Copernicus Services products.
- Enhancing opportunities for the broader European polar community to develop closer relationships with the Copernicus Services, not just with TACs.
- Ensuring independent Quality Control of services/products by establishing a continuous monitoring framework. By doing so Copernicus can independently assess improvements of

[33] https://resources.marine.copernicus.eu/documents/QUID/CMEMS-MOB-QUID-015-002.pdf

their products over time, and with the onset of new satellites, and that the Copernicus Services are returning value on the investment to European society.

- Encouraging, where possible, the publishing in peer-reviewed journals of a more academic version of the QUIDS. Independent peer-review is the bedrock of science.
- Providing recommendations from Copernicus to the European research community which clearly identifies where additional research efforts need to be focused to improve the accuracy or Cal/Val data for a particular product.

APPENDIX A: Examples of Arctic CS projects.

There is a number of CS programmes that embrace Arctic issues, INTERACT I (2011-2015) Deliverable entitled: *D8.1.1 - Information Packages and development of a Citizen Science program* highlights some examples. These include:

- Citizen Scientists contribute data: Brown bears from an INTERACT site plays important role in climate change studies
- Citizen Scientists use local knowledge to help address environmental issues
- Geocaches / EarthCaches and INTERACT
- Citizen Scientists helps with quantifying tree regeneration in the Allt a' Mharcaidh catchment, Cairngorms, Scotland
- Citizen Science projects led by the Polar Citizen Science Collective aimed at polar expedition passenger vessels: http://www.polarcollective.org/projects/

However, we would like to provide examples of two different CS activities , focusing on land and marine data collection, that we think show significant promise; (1) the monitoring of permafrost by local communities in Alaska and (2) routine ship-based observations of sea ice.

Permafrost, any ground at or below 0°C for two or more consecutive years, is the cryospheric component that is most difficult to observe from space. Unlike other cryospheric components such as glaciers, snow, and river, lake and sea ice, you cannot always tell where permafrost is present or not. However, permafrost is an important cryospheric component as it affects people living in most parts of the Arctic. When permafrost is warming and starting to thaw, it affects the stability of the ground and as a result, infrastructure can be damaged. The need for *in situ* measurements to improve the Earth Observations from space is hence large. Two existing *in situ* monitoring networks are the Thermal State of Permafrost (TSP) and the Circumpolar Active Layer Monitoring networks (CALM). The data from the TSP and CALM networks are available at the Global Terrestrial Network for permafrost's web site (http://gtnpdatabase.org/).

The Arctic is however large and to detect information needed for adaptation, more observations than is provided by TSP and CALM is needed. An example of a local Citizen Science project from Alaska that contributes with additional data needed is the "*Community based permafrost and climate monitoring in rural Alaska*" led by the University of Alaska Fairbanks (https://permafrost.gi.alaska.edu/project/community-based-permafrost-and-climate-monitoring-rural-alaska-nsf-1503900). The aim of this project is to help the tribal communities of Upper Kuskokwim region in Alaska take the lead in assessing and responding to the environmental changes that result from a warming climate and thawing permafrost. The University of Alaska Fairbanks also runs a regional Citizen Science Project throughout Alaska (https://www.nps.gov/articles/-articles-aps-v8-i1-c4.htm) which involves both villages and schools in permafrost monitoring complementing the ongoing TSP and CALM monitoring. This type of monitoring can fit in to, and benefit from, Copernicus services.

APPENDIX B: Results from INTERACT consultation

Section 1. You as a user

Q1. Does your research station use Copernicus or any other satellite data to monitor environmental change, or to help with real-time operations?

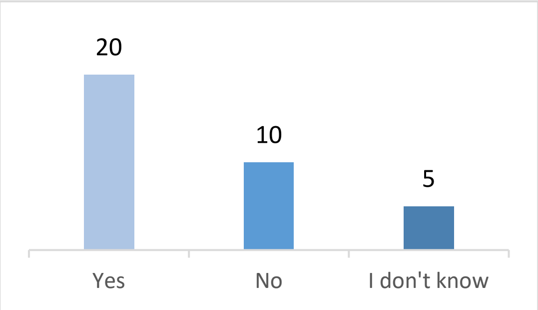

Figure 3. Responses from INTERACT community

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Q2. What are the parameters that are monitored using satellite data at your research station?

- Three participants responded “I don’t know”
- Six participants responded “None”

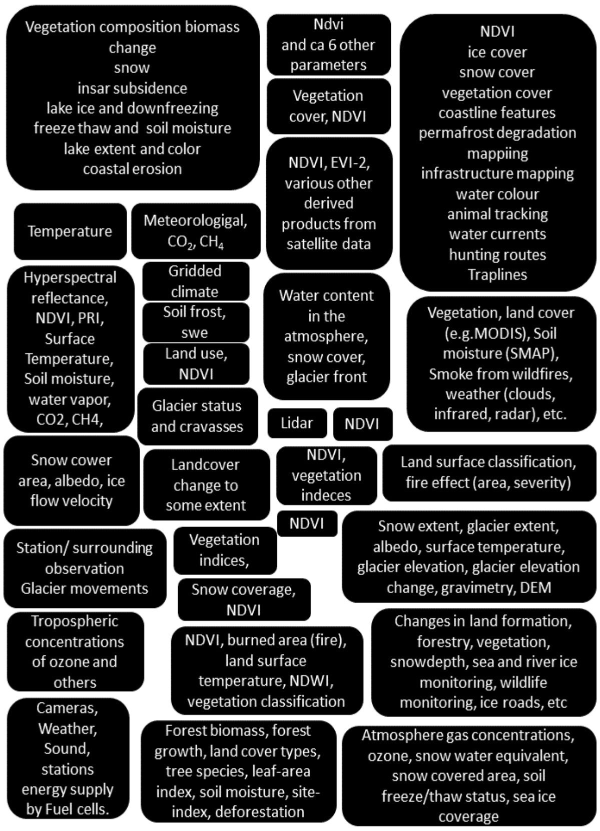

Figure 4. Responses from INTERACT community.

Q3. Is the spatial resolution adequate for the parameters you monitor using satellite data?

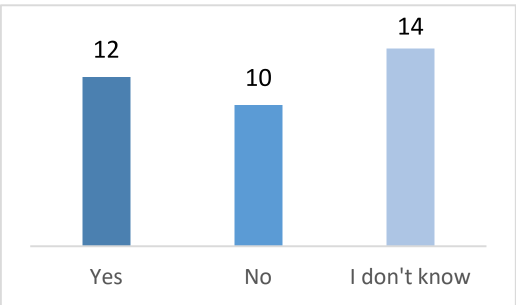

Figure 5. Responses from INTERACT community.

Section 1. You as a user (cont.)

Q4. Is the temporal resolution adequate for the parameters you monitor using satellite data?

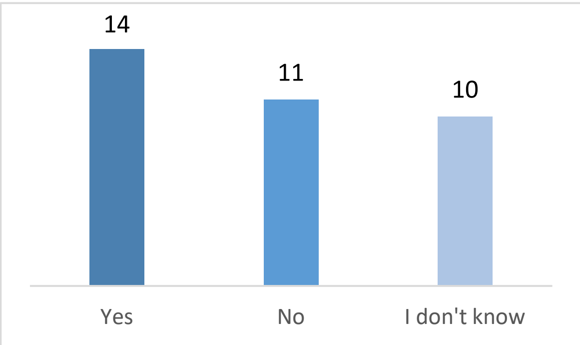

Figure 6. Responses from the INTERACT community.

Q5. Estimate the percentage of visitors to your research station that uses satellite data within their research.

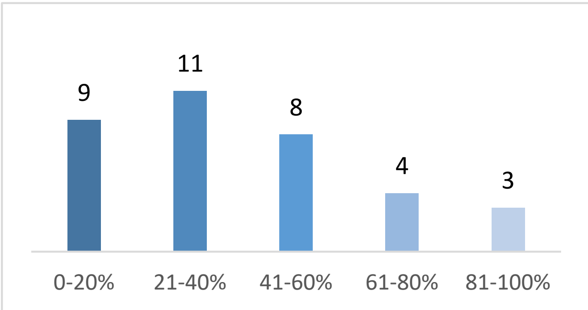

Figure 7. Responses from the INTERACT community.

Q6. Rank the importance of satellite data for current environmental studies at your research station.

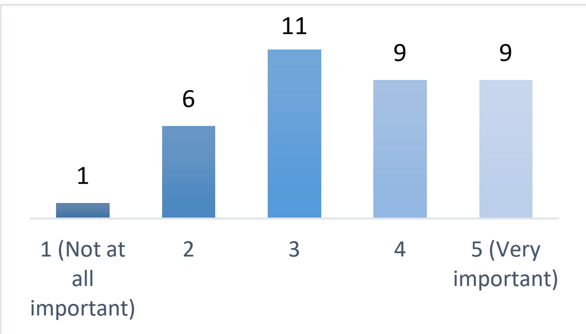

Figure 8. Responses from the INTERACT community.

Q7. Rank the expected importance of satellite data for future environmental studies at your research station.

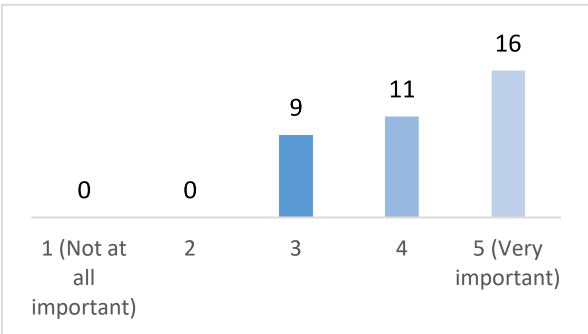

Figure 9. Responses from the INTERACT community.

Section 1. You as a user (cont.)

Q8. Are there additional parameters that you would like to monitor via satellite data at your research station?

- Three participants responded "I don't know"
- Three participants responded "No"
- Three participants responded "Yes"

Figure 10. Responses from INTERACT community.

Q9. What obstacles do you have in accessing satellite data today?

- Seven participants answered "I don't know"
- Three participants answered "No obstacles"

Figure 11. Responses from INTERACT community.

Section 1. You as a user (cont.)

Q10. What do you think are the major research gaps in satellite data in the near future (by 2050)?

- Twelve participants answered "I don't know"

Figure 12. Responses from the INTERACT community.

Q11. What are the major capacity gaps in satellite data today?

- Eleven participants answered "I don't know"

Figure 13. Responses from the INTERACT community.

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Section 2. You as a data provider for ground-truthing and operational data

Q12. Does your research station provide data for ground-truthing or for operational needs such as delivering real-time meteorological data to the GTS?

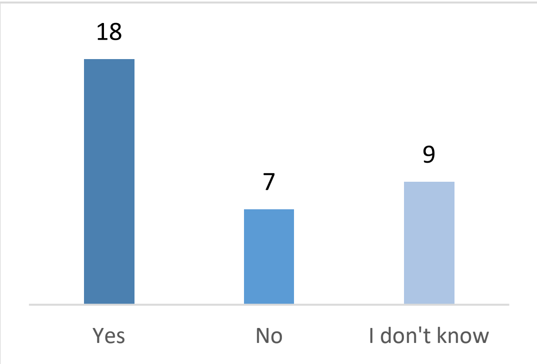

Figure 14. How many of the INTERACT Research stations that contribute with ground-truthing.

Q13. What parameters does your research station provide?

- Six participants answered “I don’t know”
- Four participants answered “None”

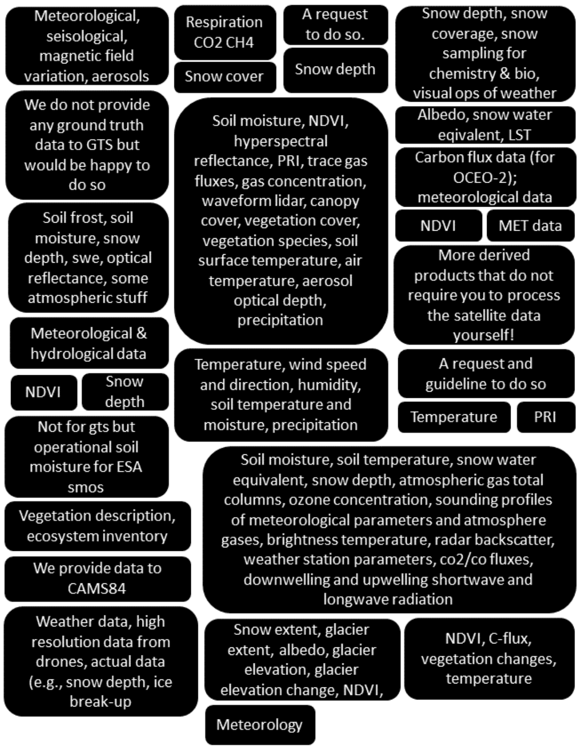

Figure 14. Parameters that INTERACT research stations provide for ground validation.

Section 2. You as a data provider for ground-truthing and operational data (cont.)

Q14. If you don't provide data for ground-truthing or operational needs, what could make you contribute in the future?

- Three participants answered "I don't know"

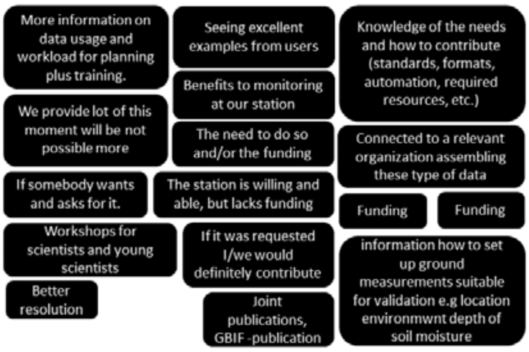

Figure 14. What would make INTERACT research stations provide more ground validation data.

Q15. How should satellite-based products evolve to better meet your research station's future needs?

- Seven participants answered "I don't know"

Figure 14. Suggestions on how to evolve products

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Additional Question/discussion

During the survey an additional question was added "Can data from drones replace satellite data at research station?"

The overall consensus was no because drones cannot fly on the same temporal resolution and over similar geographical areas as the satellite data. However, it was concluded that drone data is a valuable complement to satellite data as:

- Drone data can complement with a better spatial resolution
- Drone data can complement in cloudy conditions
- Drones can validate its data (e.g. cutting leaves from trees)