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CONNECTING SCIENCE WITH SOCIETY

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Strategic analysis of monitoring and modelling programmes

Submission of Deliverable

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Executive summary

A strategic analysis is made of current monitoring and modelling programmes in the polar regions. The analysis is based on two inventories that were produced in a preceding deliverable in the form of two Excel documents. The contents of the programmes have been mapped against EU-PolarNet's European Polar Research Priorities to determine the extent to which current programmes address prioritised objectives and key research questions. The analysis is performed both thematically and spatially to identify gaps in current programmes. We found a dominance of programmes focusing on polar biology and the polar climate system including the cryosphere, and an underrepresentation of programmes within the broad fields of human and social sciences, astronomy and space sciences, solid earth interaction, and resource management. The Arctic is substantially more represented in the inventories than the Antarctic. The analysis is finally complemented with additional input from key players and selected sources to better assess the main gaps in observations and modelling of the polar regions.

1. Introduction

Many European countries have a long tradition of conducting regular environmental observation and monitoring programmes in the Arctic and the Antarctic. These activities are often linked to major research facilities and infrastructures. They are to a varying extent coordinated by organisations such as AMAP (Arctic Monitoring and Assessment Programme) and SCAR (Scientific Committee on Antarctic Research) under the umbrellas of the Arctic Council and ATCM (Antarctic Treaty Consultative Meetings), respectively. More recently modelling programmes have been developed aimed at integrating such environmental observations into studies of spatial and temporal changes, and to set up a framework for predictions and projections of the future behaviour of polar system components.

The aim of this deliverable D2.5 is "to perform a strategic analysis of existing monitoring and modelling programmes, and the infrastructures used to deliver them, to determine where additional support may be needed to ensure the adequate collection of data to meet the needs of these programmes as well as to contribute, to the extent possible, to priority issues identified in other WP2 tasks". D2.5 directly builds on deliverable D2.3 in which an inventory was made of existing monitoring and modelling programmes, but goes somewhat beyond that by including input from key players and from selected additional sources for the identification of gaps.

The current deliverable is a contribution to Task 2.3 ("Optimisation of existing monitoring and modelling programmes") of Work Package 2 ("Polar research for Science and Society'). Within Task 2.3, the analysis will serve as input to deliverable D2.6 "Roadmap for optimisation of monitoring and modelling programmes"

2. Methodology

2.1. Inventories

At the heart of the analysis are the two inventories produced previously in D2.3. These were provided as two Excel documents for respectively observation/monitoring programmes and modelling programmes. The tables were the result of communication with representatives of national and international agencies and organisations such as AMAP, SCAR, and SOOS (Southern Ocean Observing System). They were also informed by parallel inventory work conducted by SAON (Sustaining Arctic Observing Networks) for the Arctic, as well as by a thorough internet search. Another important source of information were the members of the EU-PolarNet Consortium and the EPB (European Polar Board).

The inventories specifically list programmes as opposed to projects. To distinguish a programme from a project the following criteria were used:

- A monitoring or observational programme was defined as an activity with a broad scope and a broad geographical coverage. It is a long-term continuous activity with a broad long-lasting base for support and governance. This excludes activities with a narrow scope and shorter duration of, say, 3 years or less, which activities were labelled as a project.
- A modelling programme was defined as an overarching collaborative research initiative, often hosted or sponsored by an international organisation, and having a dominant modelling component. Such initiatives often do not carry any funding other than support for a project office and workshop meetings, but rely on research contributed by consortium or network members. This definition excludes modelling programmes run by individual institutes, or specific modelling or modelling dominated activities as part of national polar research programmes, which were both deemed too limited to be included in the inventory.

2.2. Scope and limitations

In consultation with EU-PolarNet Consortium members it was decided early on in the process to separate the programme analysis from the infrastructures required for delivering them (data infrastructures as well as physical infrastructures), as these issues are dealt with more thoroughly in Work Package 3 (“Infrastructures, Facilities, and Data”).

Other choices made in the construction of the inventories were the exclusion of monitoring programmes from space, otherwise a vast source of activities, and to focus mainly (but not exclusively) on European research or international activities with a European participation.

By construction, the scope of the current analysis is limited by the state of the inventories. The inventories reflect the status at the time of delivery in September 2016. No attempt was made to revise or update the inventories for the current analysis, even though one of the recommendations was to install a process to keep their information up-to-date. It is also realised that the inventories may be incomplete, as their contents reflect the sources that

were consulted. The choices made to include or exclude a certain activity furthermore relied on personal judgement to a certain extent.

Finally, it should be kept in mind that each of the programmes in the inventories only had concise information for a limited number of criteria (17 for monitoring programmes, 12 for modelling programmes). Only those criteria that were most readily available from the consulted sources were included. Additionally, not all individual programmes had information on all criteria.

2.3. Approach

The analysis was performed along the following lines.

Thematic analysis: the themes of the programmes were mapped against the 10 overarching European Polar Research priorities as identified in D2.1 ("Report on prioritised objectives in polar research"). In D2.1, the research priorities were further specified as bullet lists of main objectives and key research questions. Insofar the information in the inventories allowed it, this information was taken into account in the thematic allocation of a specific programme. Two more categories were added for 'Overall, international or regional programmes' and 'Other'. The latter category also contains entries that fit into the broad subject of a research priority, but are not covered by the associated objectives or key research questions.

Geographical analysis: the locations of the programmes were mapped for both polar regions. Unfortunately, a precise location under the form of a specific place name or its geographical coordinates was only available for a minority of the monitoring programmes and moreover was not included for the modelling programmes. For a number of programmes, the location information was given for a larger area (e.g. Arctic Ocean, Greenland ice sheet) and these were then plotted for the geographic centre of such an area. It is understood that overarching programmes may well cover a multitude of locations in their subprojects, but such information was not directly available from the inventories. No attempt was made to include the locations of ocean and land traverses on the maps as only fragmentary information could be accessed, yielding an incomplete picture.

Identification of gaps: this was assessed first of all from the mapping of the inventories, both thematically and geographically. To complement the analysis, input was sought from key players and from consulting additional documents:

- Input from participating in the EU-PolarNet White Paper Workshop
- Input from a limited questionnaire targeted at leads and coordinators of EU-Arctic-Cluster projects
- Input from EU-PolarNet Consortium members
- Input from global and regional organisations involved in monitoring/observational and modelling programmes

Unfortunately the response on the E-mail queries was quite low. A list of these additional contributions is given in Appendix 2.

3. Analysis of monitoring programmes

The inventory of monitoring/observational programmes had a total of 670 entries. Table 1 provides the details. Pie charts of the thematic and geographical spread are given in Figures 1 and 2.

Table 1: Number of monitoring/observational programmes in the inventory according to EU-PolarNet Polar Research Priorities and polar focus. The inventory has a total of 670 entries. Each programme may belong to more than one Research Priority. The theme allocation has been revised compared to box 6 in D2.3.

Research Priority	Arctic	Antarctic	Arctic and Antarctic	Total
Polar Climate Systems	91	46	4	141
Cryosphere	94	27	6	127
Solid earth and its interactions	-	-	-	-
Palaeoclimate and Palaeoenvironment	5	3	2	10
Astronomy, Astrophysics and Space	1	6	-	7
Human impacts	83	16	-	99
Polar Biology, Ecology and Biodiversity	145	60	-	205
Sustainable management of resources	2	-	-	2
People, Societies and Cultures	1	-	-	1
Human health and Wellbeing	12	1	-	13
Overall, international or regional programmes	13	2	2	17
Other	94	68	6	168

3.1. Thematic analysis

The most frequent programmes are those that cover *Polar Biology, Ecology and Biodiversity*, *Polar Climate Systems* and *Cryosphere*. *Human Impacts* has intermediate frequency, while *Palaeoclimate and Palaeoenvironment* and *Astronomy, Astrophysics and Space* have a low frequency. The human/social sciences *Human health and Wellbeing, Sustainable management of resources* and, *People, Societies and Cultures* all have a very low frequency. Not surprisingly the latter two are not covered in the Antarctic at all. The inventory does not contain a single programme within the scope of the research priority *Solid earth and its interactions* (Figure 1).

To first approximation, the distribution of themes covered by the monitoring programmes can be thought of as a reflection of past funding priorities, even though it gives little information on the actual distribution of the funding as the level of investment differs widely between the programmes.

The majority of the programmes deal with physical climate sciences, which includes the cryosphere. Together, this concerns 34% of all programmes. This is not unexpected in a world subjected to global warming and the crucial role played therein by the polar regions. Most of the *Polar Climate System* monitoring programmes are in fact continuous observations of

standard meteorological variables at manned stations, but also from Automatic Weather Stations and from radiosoundings. Other programmes monitor atmospheric chemistry, lake hydrology, and ocean characteristics. These observational data are required to address key research questions that identify drivers of polar climate change. The monitoring data are crucially needed to better validate ocean-atmosphere-ice-models and improve their predicting capabilities.

The monitoring programmes that focus on the *Cryosphere* deal with all forms of frozen water. The emphasis is on the Arctic, monitoring the energy and mass balance of glaciers and ice caps, mostly in Scandinavia and Svalbard, and of parts of the Greenland ice sheet. Continuous observations of sea ice thickness, permafrost, and snow cover characteristics are also well represented in the inventory. The cryospheric data contribute to the key research questions regarding the evolution and stability of glaciers and ice sheets, sea level rise, permafrost thawing, and a changing sea ice cover.

The single most abundant research theme in the inventory relates to *Polar Biology, Ecology and Biodiversity* (26% of all programmes). These cover a wide array of subjects centred on monitoring terrestrial and marine biodiversity and observing many different plant and animal species found in polar regions. Such programmes contribute to detect ecosystem changes and directly relate to key research questions addressing climate and human-related biodiversity changes, species shifts, and resilience and vulnerability of polar ecosystems. Missing from the inventory however is a specific programme to identify the severity and impacts of ocean acidification. A global network exists (goa-on.org), but it has a poor polar coverage.

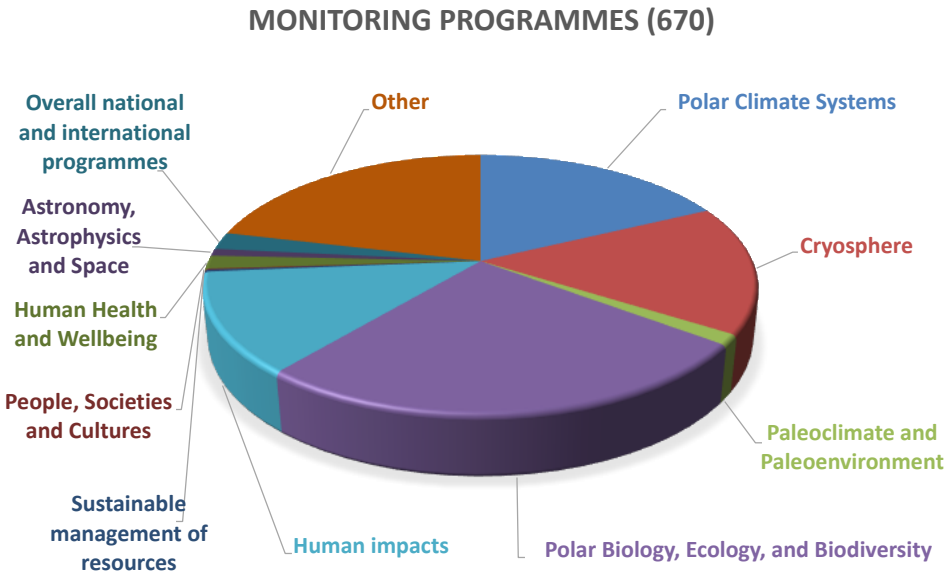

Figure 1: Relative distribution of monitoring/observational programmes in the inventory with EU-PolarNet Polar Research Priorities in their scope. The inventory has a total of 670 entries. Each programme may have more than one scope.

Programmes under the theme *Human impacts* (13% of all programmes) address monitoring of ozone, aerosols and contaminants such as heavy metals, radionuclides, particulate matter, and petroleum hydrocarbons. Most of the atmospheric and marine constituants mentioned in this particular research priority appear to be covered by at least one programme.

The monitoring inventory captures only very few programmes in the category *Astronomy, Astrophysics, and Space* (6 in the Antarctic and 1 in the Arctic). The quantity and geographical spread is probably linked to the location of observatories, which are nearly absent in the Arctic and are more abundant over the Antarctic. Monitored features include aurora's, space weather, and cosmic rays, which all address key research questions. It can however not be excluded that the monitoring inventory does not cover all relevant activities here, as some may have been missed from our search methodology.

The near absence of monitoring programmes under the theme *Paleoclimate and Paleoenvironment* is closely linked to the nature of the subject, which does not lend itself to present-day observations. The few programmes in the inventory focus on mapping the extent of past glaciations, the distribution of pollen deposition, and the managing of paleoclimate data. It is believed that this theme is much more covered by targeted projects aiming at collecting a variety of proxy records from ice and sediment cores.

Equally very poorly represented in the inventory are monitoring programmes targeting *Sustainable management of resources*. The two records in the inventory deal with the status and trend of natural resources including streamflow in national park units in Alaska. It seems clear that any potential commercial exploitation of natural and mineral resources and other industrial activity in the Arctic (the Antarctic is excluded following the provisions of the Antarctic Treaty) is not underpinned by any monitoring programme addressing the feasibility, challenges, and impacts of such activities. Such activities include fishing, exploitation of oil and gas reserves, and maritime operations in conditions of reduced sea ice.

Completely missing from the inventory are programmes addressing key research questions in the *Solid Earth and its interactions* category. There are a few programmes focusing on geodetic and geophysical observations relevant for geodynamics (gravity, geomagnetism, seismography, land uplift). But none of them address the key research questions described in D2.1, which focus on geothermal resources, plate tectonics, and volcanic activity, with an eye on the potential exploitation of natural and mineral resources in the future.

Of specific interest in the monitoring inventory are programmes focusing on human and social sciences. These are also very poorly represented. Most of these programmes (13, or 1.6% of all programmes) monitor *Human health and Wellbeing*, all of them targeting indigenous communities in Alaska, Canada, Greenland, and northern Eurasia including the Russian Arctic. The only programme recorded in *People, Societies and Cultures* deals with environmental monitoring of elements impacting on cultural remains on Svalbard and Jan Mayen.

The poor representation of programmes in the social sciences and humanities very likely reflects the lack of funding for such work. Furthermore, the relatively small number of people living in the polar regions also plays a role. Social sciences have been fairly recently picked up

by the International Arctic Science Committee (IASC) and SCAR, largely growing out of the International Polar Year (IPY) of 2007-2008. It may also be that the keywords used for searching the inventory database did not match human activities well. But our correspondents also point out intrinsic challenges and complexities in monitoring Arctic populations, in particular indigenous communities, which inhibit putting an integrated, cross-regional, long-term monitoring system in place. These challenges relate to the difficulty of translating qualitative data such as cultural empowerment and political power into quantifiable statistics, but also to the profound lack of sources for obtaining relevant quantitative data. For instance, records that are important to monitor people differ considerably throughout Arctic regions and nations in frequency of release, quality, and accuracy. Furthermore, ethnic information is often not available, which hinders intersectional analysis. In Scandinavian official registers ethnicity has been excluded since the 1960s.

Finally, the category *Other* (21% of programmes) combines all monitoring/ observational programmes that are not directly contributing to any of the research priorities defined in D2.1 of EU-PolarNet. Examples are programmes in the fields of geophysics (geomagnetism, seismology), geodesy (GPS, mapping), hydrology (ground water), and soil sciences. All *Overall, international or regional* programmes are also listed in one of the other topical research priorities.

3.2. Geographical analysis

The majority of the monitoring programmes are focused on the Arctic (73%), while 25% are from the Antarctic, and only a small fraction (2%) deal with both poles (Figure 2). This reflects the dominance of Arctic polar research over Antarctic polar research. The disparity has its roots in history, accessibility, and availability of research infrastructure. Possibly there is also

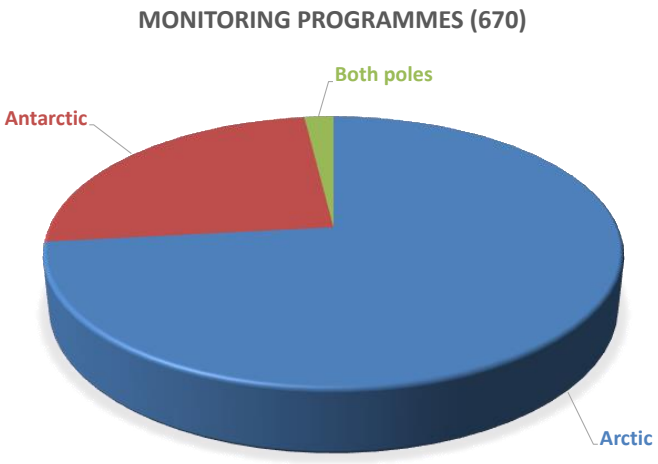

Figure 2: Number of monitoring/observational programmes in the inventory according to their polar focus.

a bias caused by the sources that were consulted to build the inventory, but this cannot be judged further.

For most of the observational programmes the inventory also contains information about geographical location. These are plotted in Figures 3 and 4, together with the locations of European facilities as listed in deliverable D3.2 “European Polar Infrastructure Catalogue”. In total the inventory contains 279 unique positions for a total of 670 programmes. A substantial amount of positions is therefore shared between different programmes. Some of the locations are very generic (e.g. Arctic Ocean) but others are very precise. It should be stressed however that the maps do not reflect the geographical coverage of all monitoring/observational activities as the programmes shown on the maps often combine many different projects, which location information is not included. A more complete view of geographical coverage can be consulted e.g. from activities such as the Trends and Effects Monitoring Programme (ATEMP) of AMAP, or the Circumpolar Biodiversity Monitoring Programme (CBMP) of the Conservation of the Arctic Flora and Fauna (CAFF). Useful interactive maps can also be accessed via the websites of ICES and INTAROS for the Arctic and SOOS for the Southern Ocean. In addition, there exists a network of repeatedly surveyed hydrographic sections in the polar oceans that is available from the World Ocean Circulation Experiment atlas (WOCE) and its follow-up programme GO-SHIP. Furthermore, the locations of moorings and buoys can be found from the Arctic Subarctic Ocean Fluxes programme (ASOF) and the International Arctic Buoy Programme (IABP). Most of these overarching activities are listed in the inventory, however without providing the locations of all subprojects.

For the Arctic region (Figure 3) the inventory contains a dominance of locations for Scandinavia, in particular Svalbard, as well as for Iceland and Greenland. Many of the programmes are linked to stations as evident from the blue circles filled with red dots. The inventory covers quite some locations in Canada and Alaska, but there is very little in Arctic

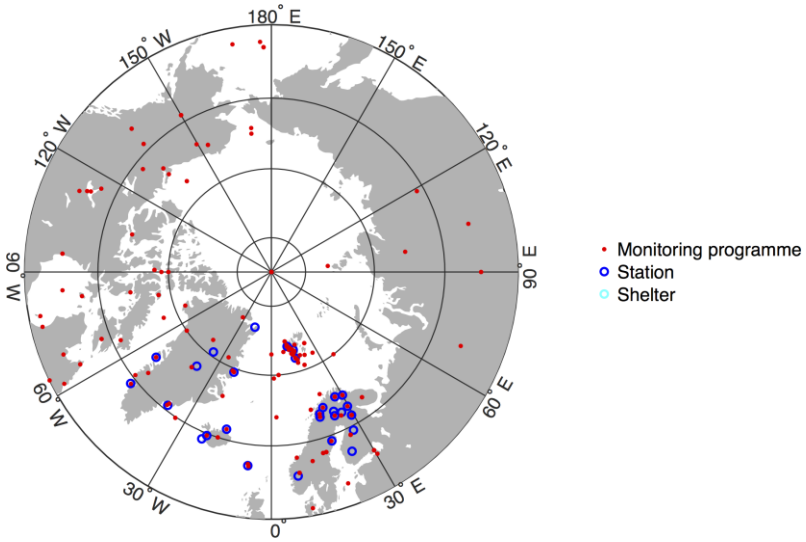

Figure 3: Locations of monitoring programmes in the Arctic are shown as a red dot. The blue circles are the locations of European research facilities. There are 147 unique locations.

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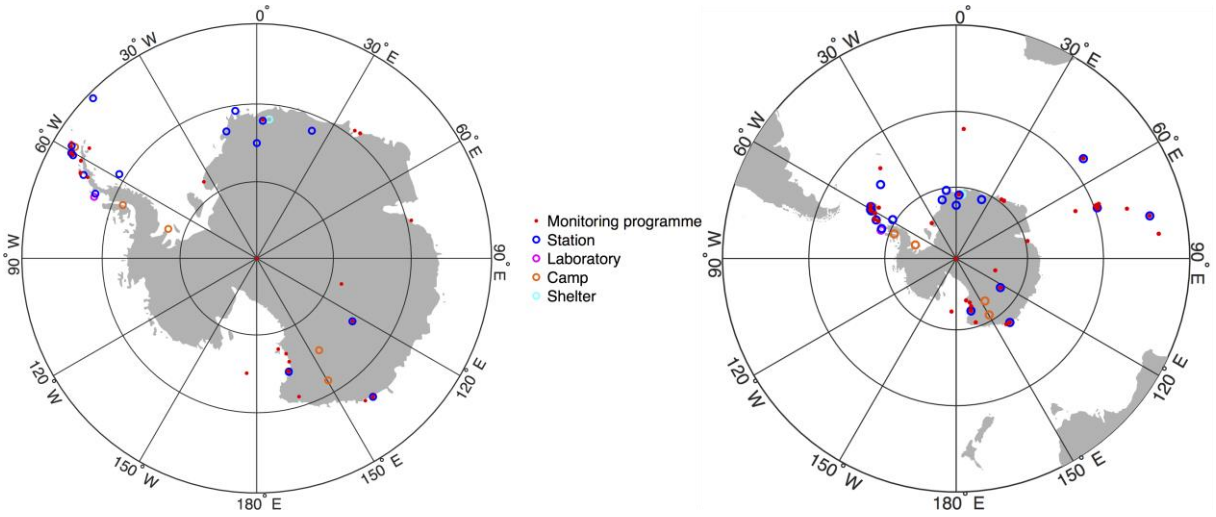

Figure 4: Locations of monitoring programmes in the Antarctic are shown as a red dot. The circles are the locations of European research facilities. There are 132 unique monitoring locations. The left figure is for the Antarctic region]south of 60°S proper. The right figure shows additional locations of programmes conducted out of subantarctic islands and French research stations in the southern Indian Ocean.

Russia. Locations in the Arctic Ocean are not specified further and are represented by a red dot at the North Pole. The absence of Russian programmes in the inventory is striking and presents a clear gap. The situation is probably a combination of limited European involvement in Russian monitoring programmes but may equally well indicate a less dense Russian observational network in the Arctic. At this stage it seems fair to say that the Russian information is incomplete.

Monitoring/observational programmes with location information in the Antarctic region are clustered on the Antarctic Peninsula and in two regions of East Antarctica: Dronning Maud Land and Victoria/ Wilkes Land (Figure 4). These are also the regions where European research infrastructures are located. Strikingly, apart from the Antarctic Peninsula, the inventory contains no programmes with location information in West Antarctica, nevertheless this is the most sensitive part of the Antarctic ice sheet where also the largest changes are taking place today. This may be attributed to the absence of European research stations in this part of Antarctica. It is worth remarking that not all European facilities are accompanied by a local observational programme centred at the station. That could point to missing information in the records but it could also indicate that such programmes do not exist, for instance because the station is only sporadically manned for a limited period of the year. The inventory has also quite some information from programmes conducted out of the subantarctic islands. The most northernmost location is Amsterdam Island (37.8°S, 77.5E), part of the French Southern and Antarctic Lands in the southern Indian Ocean. As noted above, the location of regularly surveyed hydrographic sections and land traverses are not plotted as the information at hand was incomplete.

4. Analysis of modelling programmes

Table 2: Number of modelling programmes in the inventory according to EU-PolarNet Polar Research Priorities and polar focus. The inventory has a total of 32 entries. Each programme may belong to more than one Research Priority.

Research Priority	Arctic	Antarctic	Both poles/ global	Total
Polar Climate Systems	10	4	4	18
Cryosphere	2	5	7	14
Solid earth and its interactions		1	1	2
Palaeoclimate and Palaeoenvironment	1		1	2
Astronomy, Astrophysics and Space				
Human impacts	1		1	2
Polar Biology, Ecology and Biodiversity	3	2		5
Sustainable management of resources				
People, Societies and Cultures	1			1
Human health and Wellbeing				

The inventory of modelling programmes had a total of 32 entries. Only 14 of those are pure modelling programmes, 18 programmes are linked to observations from both surface and satellite platforms. Table 2 gives more details. Pie and bar charts of their focus are given in Figures 5 to 7. A concise summary of the modelling inventory is given in Appendix 3.

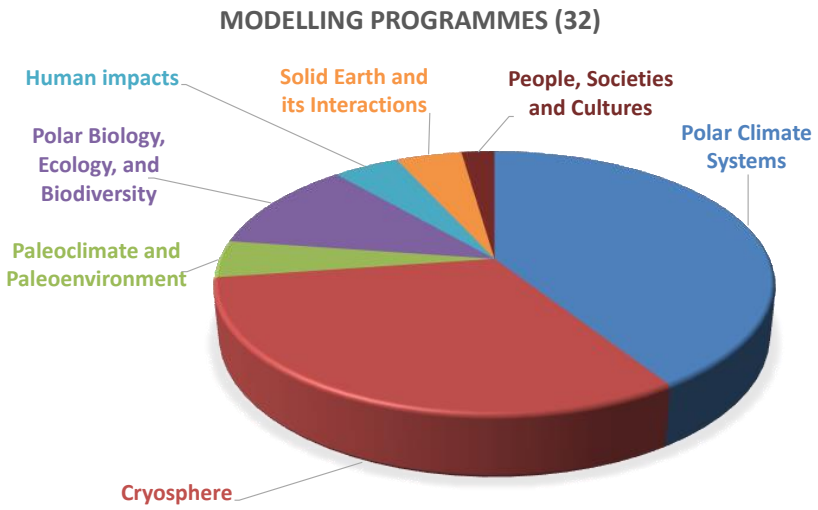

Figure 5: Modelling programmes in the inventory mapped against the EU-PolarNet Polar Research Priorities. The inventory has a total of 32 entries. Each programme may have more than one scope.

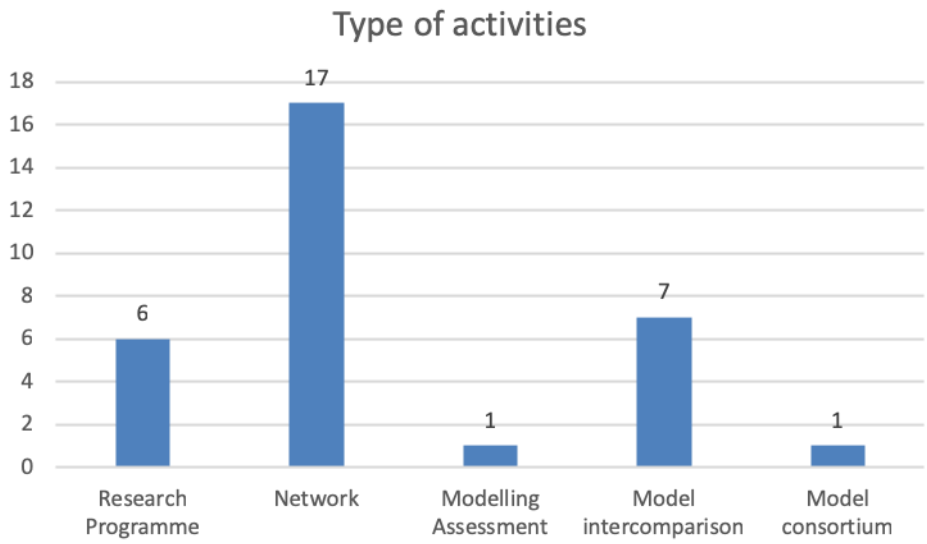

Figure 6: Type of activities deployed within the 32 identified modelling programmes.

Not surprisingly, when mapping the modelling programmes against the Polar Research Priorities, the large majority deal with the *Cryosphere* (41%) and *Polar Climate Systems* (32%), followed by *Polar Biology, Ecology, and Biodiversity* (11%). Other research themes have only a few associated modelling programmes. Several research priorities are not backed up by a modelling programme at all, partly because it does not fit within the subject. That is the case for *Astronomy, Astrophysics, and Space*, *Sustainable management of resources*, and *Human health and Wellbeing*. This does not exclude that some modelling takes place within these research themes, but a longer-lasting overarching initiative could not be identified.

A little more than half of the identified modelling programmes are in fact networks hosted by international organisations such as SCAR (where the networks are called Scientific Research Programmes), IASC, the World Climate Research Programme (WCRP), the European Climate Research Alliance (ECRA), Past Global Changes (PAGES), and the Arctic Portal (Figure 6). These initiatives generally do not carry any research funding apart from support for workshop meetings and short exchange visits. The networks tend to bring together key players and main modelling groups. Regular meetings often take place in the framework of larger science conferences, ensuring an efficient information flow and community input for developing science implementation plans. The goals of these networks address many of the key research priorities for the themes *Polar Climate Systems* (key physical and chemical processes in oceans and atmosphere, forecasting and projections of future changes) and *Cryosphere* (ice-sheet dynamics, permafrost thawing, sea level rise). For programmes within the themes *Polar Biology, Ecology and Biodiversity*, *Human impacts*, and *Paleoclimate and Paleoenvironment* modelling is usually undertaken in a supporting role and is not the main activity.

The inventory also contains 6 research programmes which are partly or fully devoted to modelling polar systems. These are longer-term initiatives funded by national or international agencies such as the EU's Horizon 2020 (H2020), the National Science Foundation (NSF), and the UK Natural Environment Research Council (NERC). In general, the goals of the modelling

performed within these research programmes align with EU-PolarNet's prioritised research objectives. Again, the emphasis of the modelling is on the physical ice and climate system, and mainly in the Arctic.

A particularly important role within the modelling community is played by model intercomparison initiatives (MIPs). The inventory includes 7 such initiatives that focus on the polar regions. GlacierMIP (glaciers), ISMIP6 (ice sheets), SIMIP (sea ice), and Polar-CORDEX (regional climate models) are initiatives hosted by the Climate and Cryosphere (CliC) office, a core project of WCRP. The latter 3 MIPs are also endorsed by CMIP6 to provide direct input for Working group I of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6), due in 2021. Within MIPs existing models are run under the same boundary conditions and model forcings to investigate their potential systematic biases, their variability and usability for projections and predictions, and their responses to detailed future scenarios such as the new Shared Socioeconomic Pathways (SSP) scenarios. Another CMIP6-endorsed MIP is the Paleoclimate Modelling Intercomparison Project (PMIP4), which focuses on comparing model simulations of historical climates for the last millennium, the mid-Holocene, the Last Glacial Maximum, the Last Interglacial, and the mid-Pliocene Warm Period. MIPs are very comprehensive exercises that are very well attended. Usually all operational models in use by the different institutes and groups participate in the experiments, with a clear dominance of European groups when it comes to polar issues.

Worth mentioning as well are two more modelling programmes in the inventory. CCI-CMUG is the Climate Model User Group of the ESA-funded Climate Change Initiative (CCI). It aims at assessing the quality and usability of satellite products in models. Relevant for polar research are the assessment of Essential Climate Variables (ECVs) for glaciers, snow, ice sheets, sea ice, and permafrost. This is a very relevant activity with applications to initialising and validating polar climate system models through data assimilation. Finally, rather than attempting to list all polar system models in use and under development at European institutions, the modelling inventory includes the EC-Earth European community Earth System Model as a prominent example of a widely used global model with many applications also in the polar research community.

The only modelling programme which has *People, Societies, and Cultures* in its focus is the NERC/FP7 funded programme ICE-ARC, aiming at assessing the social and economic impact of Arctic sea-ice loss. This programme included an economic Integrated Assessment Model. However, the activity ended in 2017.

Geographically, the distribution between both poles is more equilibrated compared to the monitoring programmes (41% are solely Arctic, 25% Antarctic). 19% of the programmes have a focus on both poles, and for another 16% of the programmes polar modelling is a subsection of global models. This of course makes sense as the polar climate system is an active interactive part of the global climate system and cannot be studied solely in isolation (Figure 7).

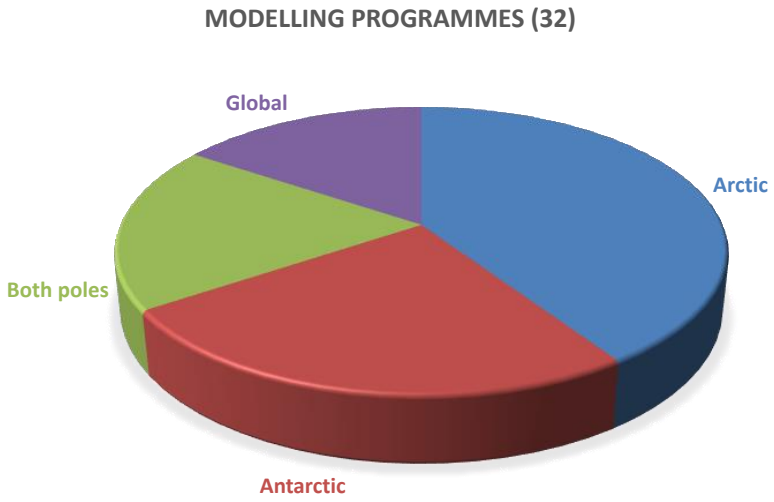

Figure 7: Number of modelling programmes in the inventory according to their polar focus.

5. Gaps in observations and modelling programmes from selected additional sources

To complement the analysis on modelling and data gaps additional sources were consulted. Various initiatives have over time described gaps in current polar monitoring/observational and modelling activities. An important assessment is the AMAP report *Snow, Water, Ice and Permafrost in the Arctic* (SWIPA, 2011). The report concludes that shortfalls in understanding and thus the ability to project future states result from insufficient data (such as observational data) and shortcomings of climate models. It notes discipline-specific gaps and issues, which should be resolved to ensure a more accurate understanding in the future.

A (non-exhaustive) list of major gaps in polar observations and modelling is summarised in Tables 3 and 4. The tables are inspired by the key findings in Chapter 11 of the SWIPA (2011) report, but have been amended and extended with additional information from own judgement and from the contributors listed in Appendix 2. The focus is on climate and cryosphere issues.

Table 3: Overview of major gaps in polar observations modified and extended from the key findings in AMAPs SWIPA (2011) report, section 11.5.

Major gaps in polar observations	
Ocean	
Sea ice extent	In situ coverage is sparse and incomplete
Sea ice concentration	Potentially large uncertainties in satellite retrievals in summer
Sea ice thickness	Satellite methods are still developing; snow depth on ice is an unknown
Sea ice motion	Important small-scale motions not captured by satellites; in situ measurements sparse
Snow depth on ice	Satellite method is limited to first-year ice with potentially large uncertainties; in situ data are sparse
Surface temperature	Uncertainty in satellite estimates due to cloud cover
Albedo	Sparse in situ coverage; significant uncertainty
Carbon cycle	Poor characterisation of air-sea and air-sea ice carbon fluxes and the seasonal carbon cycle.
Terrestrial	
Snow cover	In situ network is declining
Snow depth	Satellite method is limited to tall-grass prairie
Snow water equivalent	In situ coverage is sparse
Freshwater ice	Declining observation network
Glacier, ice cap, ice sheet thickness	Incomplete coverage, especially for smaller-scale features such as (outlet) glaciers and many small ice caps
Glacier, ice cap, ice sheet motion	Short temporal records and incomplete coverage
Permafrost: ground temperature	Large portions of the Arctic not covered
Permafrost active layer thickness	Large portions of the Arctic not covered
Permafrost: borehole temperature	Records are discontinuous and short. Data rescue efforts needed for historical data extending back 50 to 100 or more years
Permafrost: regional gaps	Significant thematic and regional gaps in eastern and central Canada, most ice-free areas in Greenland, and north-central and northeastern Russia
Surface temperature	Satellite method is clear sky only
Albedo	Sporadic in situ coverage
Atmosphere	
Precipitation	Current precipitation gauge networks are sparse
Contaminants	Short and topic-specific records; atmospheric chemistry data difficult to obtain from Russia
Surface-based observation networks	Declining observation network; many important observation and monitoring efforts are project- based and in need of sustained funding

Table 4: Overview of major gaps in polar climate modelling modified and extended from the key findings in AMAPs SWIPA (2011) report, section 11.5.

Major gaps in polar climate modeling	
Sea ice	Unrealistic representation of sea ice in both hemispheres; sea ice deformation has wrong spatial and temporal variations; landfast ice and polynyas not well represented.
Ocean Circulation	Major current systems, deep water formation, polar-midlatitude linkages and meso-scale features such as ocean eddies are not adequately represented.
Missing processes in climate models	Ocean waves, icebergs, sea ice biogeochemistry, permafrost.
Coupling between the ocean and ice sheets	Poor representation of ice melting in ice-shelf cavities and at calving fronts
Polar atmospheric boundary layer	Lack of full coupling between surface dynamics and the atmosphere. More accurate incorporation of surface albedo and snow microphysics needed.
Clouds	Vertical and horizontal distrubution of clouds are poorly represented
Downscaling	Atmospheric downscaling techniques need improvement to provide information at relevant scales for regional modeling and decision makers
Snow	Inadequate models of snow-vegetation interactions
Permafrost	Underrepresentation of the ice content and the organic layer. Failure to adequately represent the disequilibrium that has arisen because some current permafrost is related to past climates.
Glaciers	Glacier mass balance models need improvement
Greenland ice sheet	Inadequate representation of ice dynamics near calving fronts and at the bed
Antarctic ice sheet	Key uncertainty is the mechanical response of the grounding line to changes in the ice shelves
Model initialisation and validation	Data assimilation capacity using satellite data needs further development (all components)
Model resolution	Enhanced predictions and projections need a step change in horizontal and vertical resolution
Model coupling	Representation of complex interactions and feedbacks between components of the polar climate system require a full interactive coupling of atmosphere-ice-ocean models

6. Conclusion

The analysis brought to light the overwhelming dominance of natural sciences (cryosphere, atmosphere, ocean, and land) and to a lesser extent biological sciences in the monitoring/observational and modelling programme inventories of polar research. This is not unexpected since both disciplines link to global climate change and its consequences and have traditionally been the main beneficiaries of research funding. On the other hand, there is very little about space sciences, health, and human and social sciences. Several of EU-PolarNet's European Research Priorities are therefore hardly or not covered by current monitoring and modelling programmes. That is the case for the key research questions contained in the themes *Astronomy, Astrophysics and Space*, *Sustainable management of resources*, *Solid Earth and its interactions*, *Human health and Wellbeing*, and *People, Societies and Culture*. In particular the latter gap can be explained by specific challenges for data collection in addition to a lack of funding in the past.

Geographically, Arctic programmes dominate over Antarctic programmes in number and scope by a ratio 3:1 on average, and this is more outspoken for monitoring programmes than for modelling programmes. Specific regional gaps in the listed programmes concern large parts of the Russian Arctic, West Antarctica, and East Antarctica south of the Indian Ocean. These are also the regions where European scientific involvement is minimal or absent.

It should however be kept in mind that the analysis is by nature limited by the contents and scope of the inventories. Flaws in the analysis therefore necessarily reflect shortcomings in the construction of the inventories. It is possible that important programmes were missed making the analysis less complete. This should be picked up in a potential follow-up project that could also set up a framework for keeping the inventories up-to-date.

Appendix 1: List of acronyms

AMAP: Arctic Monitoring and Assessment Programme
ASOF: Arctic Subarctic Ocean Fluxes programme
ATEMP: AMAP Trends and Effects Monitoring Programme
ATCM: Antarctic Treaty Consultative Meetings
AWS: Automatic Weather Station
CAFF: Conservation of the Arctic Flora and Fauna
CBMP: Circumpolar Biodiversity Monitoring Programme
CliC: Climate and Cryosphere
CMIP: Climate Model Intercomparison Project
ECRA: European Climate Research Alliance
ECV: Essential Climate Variable
EPB: European Polar Board
ESA: European Space Agency
GlacierMIP: Glacier Model Intercomparison Project
GO-SHIP: Global Ocean Ship-based hydrographic investigations program
H2020: EU Horizon2020
IABP: International Arctic Buoy Programme
IASC: International Arctic Science Committee
INTAROS: Integrated Arctic Observation System
IPCC AR6: Sixth Assessment Report of the Intergovernmental Panel on Climate Change
ISMIP: Ice Sheet Model Intercomparison Project
MIP: Model Intercomparison Project
NERC: Natural Environment Research Council
NSF: National Science Foundation
PAGES: Past Global Changes
Polar-CORDEX: Polar Coordinated Regional Climate Downscaling Experiment
PMIP: Paleoclimate Modelling Intercomparison Project
SAON: Sustaining Arctic Observing Networks
SCAR: Scientific Committee on Antarctic Research
SIMIP: Sea Ice Model Intercomparison Project
SOOS: Southern Ocean Observing System
SWIPA: Snow, Water, Ice and Permafrost in the Arctic
WCRP: World Climate Research Programme
WOCE: World Ocean Circulation Experiment

Appendix 2: List of additional contributions

2.1 Names of individuals external to EU-PolarNet that were contacted by E-mail and provided input

Contributor	Role	Type of information
Chiara Bearzotti	Project manager of H2020 Blue-Action	Gaps in North-Atlantic and Arctic surveys
Thomas Jung	Project coordinator of H2020 APPLICATE	Gaps in Arctic climate modelling
Hugues Lantuit	Project coordinator of H2020 Nunataryuk	Data and knowledge gaps in Arctic permafrost
Daniela Liggett	Human geographer at University of Canterbury, New Zealand	Assessment of lack of human and social science programmes
Louise Newman	Executive officer of SOOS	Gaps in Southern Ocean data and knowledge
Steffen Olsen	Project coordinator of H2020 Blue-Action	Gaps in polar climate modelling
Tuukka Petäjä	Project coordinator of H2020 iCUPE	Data gaps in Arctic aerosols
Stein Sandven	Project coordinator of H2020 iNTAROS	Gaps in Arctic observing systems
Peter Sköld	Executive director of Arctic Research Center at Umeå University, Sweden	Assessment of lack of human and social science programmes

2.2 Consulted reference for additional information on modelling and data gaps

Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere, AMAP, Oslo, 2011, 553 p.

Appendix 3: Concise version of the modelling inventory

Acronym	Host organisation	Theme	Region	Activity
APPLICATE	EU H2020/ AWI	Polar Climate Systems	Arctic	Research Programme
AGP	NSF	Cryosphere	Antarctic	Research Programme
AnT-ERA	SCAR	Polar Biology, Ecology and Biodiversity	Antarctic	Network
AntClim21	SCAR	Polar climate systems; Cryosphere	Antarctic	Network
AOAS	NSF	Polar Climate Systems	Antarctic	Research Programme
Arctic ECRA	European Climate Research Alliance	Polar Climate Systems	Arctic	Network
Arctic-HYDRA	Arctic Portal	Polar Climate Systems	Arctic	Network
ARCTrain	Université du Québec à Montréal	Polar Climate Systems, Cryosphere	Arctic	Network
ART	International Arctic Research Center	Polar Climate Systems; Polar Biology, Ecology and Biodiversity	Arctic	Network
Blue-Action	EU H2020/ DMI	Polar Climate Systems	Arctic	Research Programme
CAO	NERC	Polar Climate Systems; Polar Biology, Ecology and Biodiversity	Arctic	Research Programme
CCI CMUG	ESA	Polar Climate Systems, Cryosphere	Global	Modeling Assessment
CCMI	WCRP/IGAC/SPARC	Human Impacts	Global	Network
EC-Earth	ECMWF	Polar Climate Systems	Global	Model consortium
ESSAS	Havforskningsinstitutett	Polar Biology, Ecology and Biodiversity	Arctic	Network
FAMOS	Woods Hole Oceanographic Institution	Polar Climate Systems	Arctic	Model Intercomparison
GlacierMIP	WCRP/CliC	Cryosphere	Both	Model Intercomparison
ICE-ARC	NERC/FP7/BAS	Polar Climate Systems; People, Societies and Cultures	Arctic	Research Programme
ICED	SCAR/IGBP/BAS	Polar Climate Systems; Polar Biology, Ecology and Biodiversity	Antarctic	Network
ISMASS	SCAR/IASC/CliC	Cryosphere	Both	Network
ISMIP6	WCRP/CliC	Cryosphere	Both	Model Intercomparison
MISOMIP	WCRP/CliC	Polar Climate Systems, Cryosphere	Antarctic	Model Intercomparison
PACES	NOAA/Leeds/CNRS(LATMOS)	Human impacts	Arctic	Network
PAIS	SCAR	Cryosphere	Antarctic	Network
PALSEA	PAGES/INQUA	Cryosphere; Solid Earth and its interactions	Global	Network
PAST Gateways	Lund University	Palaeoclimate and Paleoenvironment	Arctic	Network
PCN	University of Alaska	Polar Climate Systems, Cryosphere	Arctic	Network
PMIP	PAGES/CLIVAR	Palaeoclimate and Paleoenvironment	Global	Model Intercomparison
Polar-CORDEX	WCRP/CliC	Polar Climate Systems	Both	Model Intercomparison
PPP	WMO/WCRP/WWRP	Polar Climate Systems, Cryosphere	Both	Network
SERCE	SCAR	Solid Earth and its interactions, Cryosphere	Antarctic	Network
SIMIP	WCRP/CliC	Cryosphere	Both	Model Intercomparison